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INVESTIGATION OF POROUS PAVEMENTS FOR URBAN RUNOFF CONTROL

Edmund Thelen, et al

Franklin Institute Research Laboratories

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INVESTIGATION OF POROUS PAVEMENTS
FOR URBAN RUNOFF CONTROL

by

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ABSTRACT

Laboratory and economic studies were undertaken to determine the feasibility of utilizing porous pavements to alleviate combined sewer overflow pollution and reduce the design parameters of storm sewer systems by allowing storm runoff to percolate back into the ground.

Laboratory studies of candidate materials revealed a porous asphaltic concrete containing 5.5% asphalt by weight and aggregate graded to allow a water flow of 76" per hour to be the optimal porous road material. Materials testing for stability, durability, and freeze-thaw susceptibility proved this material suitable for use in road construction.

Asphalt Institute specifications were used to design roads with porous asphaltic concrete surfaces and gravel bases for varying traffic densities. Major design parameters considered were the load-bearing capacity and permeability of the subgrade, expected maximum precipitation and depth of frost penetration.

Roads designed with porous asphaltic concrete were found to be generally more economical than conventional roads with storm sewers. The economics of porous pavement were further enhanced by the added value of benefits from combined sewer overflow pollution relief, augmentation of municipal water supplies, improved traffic safety, preservation of vegetation, relief of flash flooding and the aesthetic and directional benefits of a colored porous surface.

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SECTION I

CONCLUSIONS

Objectives and Benefits

The investigation of porous pavements was undertaken primarily because of the potential of porous pavements for alleviating combined sewer overflow pollution. Over-flow pollution is currently a problem for the approximately 18% of the nation's population served by combined sewers. During storms, interception sewer capabilities are too small to handle the volume of flow generated, and the major portion of the stormwater is outflowed directly into receiving watercourses. These stormwater outflows carry with them as much as 25 to 40 percent of the year's production of suspended solids, putrescible organic matter, and bacteria, which tend to settle at the bottom of a sewer to be swept up and out untreated to surrounding watercourses by the stormwater overflow. The delivery of these untreated pollutants contributes significantly to the pollution of surrounding waters. Porous pavement, by allowing stormwater to percolate into the soil rather than overflow combined sewer systems, could alleviate much of this pollution.

Further, where separate storm sewer systems already exist or are to be installed, the use of porous pavement could produce substantial cost savings. In the former case, the use of porous pavement could alleviate the need to install additional capacity where the present storm-sewer systems capacity is fully utilized. In the latter case, the use of porous pavement would allow reduction in the design parameter of the storm drainage collection system installed.

In addition to the primary objective of finding a means of eliminating combined sewer pollution, as well as reducing the cost of storm drainage collection systems, a number of other benefits were found to result from porous pavement applications. These benefits are identified separately below:

1. Storm-Water Retention. Evidence on the polluted character of stormwater indicates that it may be necessary in the future to store such water for subsequent treatment when system capacity is available. The construction of porous pavement over an impervious membrane offers a potential mechanism of storing polluted stormwater and slowly releasing it for subsequent treatment.

2. Enhanced Water Supply. Substantial areas of the country are now subject to water supply deficiencies. By allowing precipitation to percolate back into the soil, the use of porous pavement could help to alleviate water supply problems for the 24% of the nation's population currently clustered in water shortage areas. This is particularly important since existing water-transfer agreements will not be able to supply the demand in many of these areas past the end of the century.

3. Elimination of Curbing. Curbs and gutter could be eliminated on low traffic density porous pavements, effecting considerable cost economies as well as aesthetic enhancement.

4. Safety Improvement

   a. Skid Resistance. Porous pavement overlays on conventional surfaces have been found successful in preventing wet skidding or hydroplaning accidents. For safety application a 3/4" to 1" layer over normal dense pavement is used to provide rapid lateral surface drainage. Such applications have been used successfully on road surfaces in California, Louisiana, Utah, and Pennsylvania and airport runways in England and New Mexico.

   b. Enhanced Visibility. Visibility of pavement markings is expected to be improved because of rapid removal of water and because of the marking material penetrating the voids to present an oblique view. The enhanced visibility of pavement markings would be an important factor in accident mitigation during storms.

5. Use of Urban Debris. The porous pavements designed will require a base reservoir capacity. There is the possibility that this reservoir can be created using broken bricks, ceramic wastes, solidified fly ash and other solid urban residue.

6. Low Maintenance Cost. As the recommended porous pavement design consists of currently used road materials, maintenance costs should not exceed the level of expense currently incurred.

7. Relief of flash flooding. About 300 square miles of new pavement of all types is laid in the United States each year. Runoff from such pavement may contribute to local floods downstream, which can cause loss of life and property. Flash flooding presents an ecological problem where storm water from large paved areas is drained off directly into neighboring streams or other small water courses. This practice produces considerable flash flooding and stream bed erosion during periods of heavy rainfall. Porous pavement would prevent this flash flooding and preserve local streams from erosion.

8. Preservation of Vegetation. Plants and vegetation along conventional roads, particularly in areas of high pavement densities, are often starved for water because the dry soil under the roads tend to rob their supply. Porous pavement would restore natural moisture to the benefit of roadside vegetation.

9. Preservation of Natural Drainage Patterns - In contrast to impervious surfaces, porous pavement would preserve natural drainage patterns. It is desirable to preserve natural drainage patterns where paving is imposed on otherwise open areas whose natural character is worth preserving and/or areas where the surfacing will be only temporary.

10. Temperature and storm control. In dense urban areas a light colored pavement would provide a cooling effect. Further, the heated air from large expanses of dark asphalt paving is suspected by meteorologists of causing thunderheads to develop on summer afternoons. This may cause moisture-laden air to dump its water on the cities where it loads the sewers, rather than carrying it over to the farmlands beyond. A light-colored pavement should not have this effect.

11. Color Infusion. A demand for colored porous surfaces was evidenced in a wide variety of applications. Laboratory tests indicated that colored roofing granules applied to a porous surface offer a promising colored pavement at economical costs of 35¢ to 60¢ per square yard, but further field evaluation of the color's durability are required. The use of naturally colored aggregates would provide a satisfactory colored surface, but their use would be economically limited to areas where colored aggregates occur naturally. The use of light colored binders in place of an asphalt binder was reported to be unsatisfactory because of a tendency of dirt to adhere to the binders and because of evidence of low durability.

12. The presence of puddles in parking lots and other areas traversed by pedestrians, is not to be expected with porous pavements.

Formulation and Test

A variety of conventional and unconventional materials were considered and the most promising ones tested to determine their physical and economic feasibility as porous pavement materials. An open-graded asphalt concrete was selected as the most suitable material because of its superior physical characteristics, its low cost, and its ability to be laid by conventional paving methods. Porous portland cement surfaces were found unsuitable because of pavement failure cause by the shifting and settling of the subgrade under the load application point. Artificial turfs were found insufficiently permeable for porous playground pavements. A resilient porous surface of adhesively bonded chopped rubber, intended for playground use, exhibited suitable physical characteristics, but was judged too expensive for more than very limited use. Similarly, pavements assembled at the site from factory-made components such as bricks or honeycombs, were seen to be uneconomical.

Porous asphalt concrete can be mixed in usual hot mix plants, and compacted and laid with the machines customarily used for asphalt concrete paving.

Three types of porous asphaltic concretes, corresponding to Asphalt Institute, British, and California aggregate specifications, were analyzed. Because of differences in size-of-aggregate specifications, the infiltrations rates of these types varied from less than 5"/hr. to more than 25"/hr. Each type was examined with asphalt binder contents of from 4.0% to 5.5% of total weight.

The most porous of the open-graded asphalt concretes contained aggregate graded in accordance with a California specification:

Sieve	Opening (MM)	Specification	FIRL Product
1/2"	12.7	100	100
3/8"	9.51	90-100	97
#4	4.76	35-50	34
#8	2.38	15-32	16
#16	1.19	0-15	13
#200	.074	0-3	2

Five and one-half percent by weight of 85-100 penetration road asphalt was the binder of choice. It is customary, when designing a pavement, to test the asphalt-aggregate mix for its resistance to stripping by water using ASTM D 1664. If the estimated coated area is not above 95% in this test anti-stripping agents are added to the asphalt.

Marshall stability tests were performed on all specimens to determine their load-bearing suitability in road use. All specimens considerably exceeded the minimum Marshall stability criterion for medium traffic uses.

Freeze-thaw tests were conducted to determine whether porous asphaltic concrete could withstand normal climatic cycles. Two samples each of the Asphalt Institute, British and California specifications were subjected to 265 freeze-thaw cycles. No physical dimensional changes were noted for any of the samples after the test cycles, nor was there any impairment of Marshall stability values or flow rates.

Durability tests were conducted to determine whether the heightened exposure to air or water would produce excessive asphalt hardening which would cause cracks to form in the road surface. Only the California mix with 4.5% asphalt concrete exhibited excess hardening, due mostly to its highly open structure. The California specification with 5.5% asphalt content, however, proved to combine high durability and high permeability, and was selected as the optimal porous asphalt concrete surface.

Further tests were conducted to determine the effect of porous pavement on the survival of aerobic soil bacteria. It was deemed important that these aerobic bacteria flourish under porous pavement to metabolize oils, animal and bird excrements, and other organics that might otherwise tend to clog the system or pollute the water. Rather sketchy tests for aerobic activity in soil located underneath porous asphaltic concrete revealed no inhibition of these bacterial processes.

Design of Porous Asphaltic Concrete Roadways

The design of porous asphalt concrete roadways equivalent to conventionally constructed roads was found to depend primarily on the load-bearing capacity of the subgrade, the expected traffic volume and the reservoir capacity of surface and base. Specifications of the Asphalt Institute were used to design the porous pavement roadways illustrated in the table below:

Requirements for Surface and Base Course

		Surface Thickness	Base Thickness	Reservoir Capacity (inches of rainfall)		
CBR	DTN	(IN)	(IN)	Surface	Base	Total
2	1	4	6	.60	1.80	2.40
2	10	4	12	.60	3.60	4.20
2	20	4-1/2	13	.66	3.90	4.56
2	50	5	14	.75	4.20	4.95
2	100	5	16	.75	4.80	5.55
2	1000	6	20	.90	6.00	6.90
2	5000	7	22	1.05	6.60	7.65

Because of the low load-bearing capacity of a wet subgrade a poor subgrade (California Bearing Ratio = 2) was assumed in establishing these designs. Traffic volumes are indicated by the Design Traffic Number (DTN). Traffic volumes are designated by the DTN reading as follows: 1-10, light traffic; 10-100 medium traffic, 100-5,000 heavy traffic (primarily highway.) The gravel base depths are minimums provided by Asphalt Institute specifications. These minimum base depths would have to be increased in designing porous pavements for areas where the expected maximum precipitation exceeds the indicated surface and base reservoir capacities. Thus for an expected 5.4" maximum precipitation in one hour, typical of Philadelphia, the minimum base thickness for all types of uses would have to be 16". Adding additional base thickness is relatively cheap and does not greatly affect the economic feasibility of porous pavement.

It was judged that a soil permeability of .042, sufficient to remove a 5-inch rainfall in ten days, would prove adequate for most uses. In areas with high rainfall in combination with soils of low water infiltration rates, less than 0.02 inches per hour, consideration should be given to either penetrating the low permeability soil layer by sand or other type of drain if a higher permeability soil horizon lies beneath, or by constructing nearby storage ponds to retain the water until infiltration can occur. With the latter eventuality, water penetrating the pavement layer would run off laterally to be drained to the ponds.

Economic Evaluation of Porous Asphaltic Concrete Pavements

The economic analysis undertaken determined by pavement type the cost of porous asphalt concrete in relation to conventional pavements with storm sewers, the relative value and market for the identified benefits of porous pavement, and the annual demand for the pavement types considered. Cost estimates for porous asphaltic concrete were based on Asphalt Institute specification assuming the minimum base reservoir capacity of 16" that would be required in a medium precipitation area like Philadelphia and assuming an average winter frost penetration level. Where the total thickness of surface and base exceeded conventional pavement thickness, an allowance was made for extra excavation costs. In areas of higher or lower precipitation, the cost of porous asphaltic concrete construction would be correspondingly increased or decreased somewhat, because of changes in required base reservoir capacity. Similarly, in areas of heavy frost susceptibility deep gravel bases normally are required to prevent freeze-thaw heaving, and the cost of porous construction would be correspondingly more favorable.

The results of the economic analysis are summarized in Table 1. In most cases the cost of conventional pavement with storm sewers was found to be higher than the cost of an equivalent porous asphaltic concrete installation. Except for combined sewer pollution relief and water supply enhancement, the benefits attributable to porous surfaces are specific to the type of pavement and are discussed separately by type of use.

The analysis of the economic benefit of combined sewer relief involved consideration of a wide variety of corrective measures covering a broad range of costs. Sewer separation was found to be the most frequently adopted measure with costs averaging $10,200 per surface acre, but escalating rapidly in high density areas. Separate road sewer systems have been constructed in Toronto and other cities to relieve overflow pollution at an average cost of $7,000 per surface acre in 1960 prices. Numerous less costly measures - screening, chemical treatment, off-system storage and sedimentation ponds - have also been undertaken at an average cost estimated by the America Public Works Association at $5,100 per

Table 1

POROUS PAVEMENT BENEFITS

Type of Pavement	Annual Demand (1000 y^2)	Conventional Pavement with Drainage ($\$/y^2$)	Porous Pavement ($\$/y^2$)	Combined-Sewer Relief		Water Supply		Color Infusion	
				Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)
Parking Lot	45,986	4.73	6.36	18	5.54	24	0.15 - 0.42	20	1.00
Residential Street									
Low-design	133,425	7.20	6.35	18	5.54	24	0.29 - 0.83	40	0.30 - 0.40
High-design	12,129	10.23	6.38	18	5.54	24	0.32 - 0.92	10 - 25	1.00
Business Street									
Suburban Development	52,547	8.40	6.38	18	5.54	24	0.29 - 0.83	<5	1.00 - 1.50
City	4,776	18.20	7.66	18	5.54	24	0.32 - 0.83		
County Road									
Low-volume	193,623	9.20	6.44	18	5.54	24	0.29 - 0.83	<5	0.50 - 1.75
Moderate-volume	203,864				5.54	24	0.33 - 0.84		
Highway									
Two-lane	141,955	14.50	7.36	18	5.54	24	0.33 - 0.84		
Four-lane									
Asphalt	104,023	23.88	8.48	18	5.54	24	0.33 - 0.84	[5 - 10	2.50 - 3.50]
Concrete		25.83	8.64	18	5.54	24	0.39 - 1.12		
Playground	4,397	4.55	6.34					80	1.00 - 2.20

Table 1 (Cont.)

POROUS PAVEMENT BENEFITS

Type of Pavement	Natural Drainage Preservation and Flash Flood Relief		Preservation of Vegetation		Elimination of Curbing	
	Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)
Parking Lot	<5	1.00 - 200	<5	0.50 - 1.00		
Residential Street						
Low-design			<5	0.50 - 1.00	85	1.50 - 2.40
High-design			10 - 25	0.50 - 1.00	50	1.50 - 2.40
Business Street						
Suburban Development						
City						
County Road						
Low-volume			<5	0.50 - 1.00		
Moderate-volume						
Highway						
Two-lane						
Four-lane						
Asphalt						
Concrete						
Playground						

acre. The economic value of porous pavement for eliminating overflow pollution was computed conservatively at the lower figure of \$5,100/acre, or an average of \$5,54/y^2 of pavement surface, based on a 19% pavement-to-surface area ratio. This economic benefit would apply to the 18% of the nation currently served by combined sewers.

By using porous pavement to divert stormwaters into the ground rather than into a sewage system, the need for building treatment plants can be mitigated and an additional substantial saving can be realized over and above the savings reported above.

Water supply benefits are imputable to the 24% of the nation's population located in water deficit areas. The value of the additional water was evaluated at 30¢ to 60¢ per 1000 gallons, equal to the cost of imported water under current water transfer arrangements. Discounted over the pavement surface life, the value of this benefit would range from 15¢ to \$1.12 per square yard of pavement surface.

The economic benefit of other porous characteristics are specific to the type of pavement and are indicated in the economic analysis by type of pavement below:

Parking Lots

Annual demand for parking surfaces was estimated at approximately 46 million square yards per year. Cost of porous parking areas was estimated to average \$6.36 in contrast to \$4.73 per square yard for conventional surfaces with storm sewers. The unfavorable relative cost differential results largely from the relatively high Asphalt Institute specifications in contrast to the low-level conventional designs typically installed.

Color differentiated parking spaces would command a \$1 per square yard premium in about 20% of the market. The relief of flash flooding would command a premium of \$1/y^2 to \$2/y^2 in the less than 5% of the market where legislation to curb flash flooding has been enacted. The market for this benefit should expand considerably as more areas pass legislation controlling flash flooding. A very limited demand with an estimated economic value of 50¢/y^2 to \$1.00/y^2 was evidenced for the use of porous pavement to preserve vegetation in parking lots.

Residential Streets

Two types of residential streets were considered: low-design, typical of suburban areas and high-design, typically observed only within large cities. The relative costs for porous and conventional design with storm sewers were \$6.35/y^2 vs. \$7.20/y^2 and \$6.38/y^2 vs. \$10.23/y^2 for low and high design respectively. Urban planners indicated that color would be desired in 40% of the low-design market if it could be produced between 30¢/y^2 and 40¢/y^2. Color infusion was desired in 10% to 25% of the high design residential market, depending on the level of urban-renewal activities, where the combination of aesthetic and temperature control benefits would command a premium of \$1/y^2. Porous pavement for vegetation preservation would have only limited applicability in low-density suburban areas, but would command an economic premium in a significant fraction of the city residential street market. The elimination of curbing would save between \$1.50/y^2 and \$2.40/y^2 in residential areas. This benefit would affect most of the suburban residential market, but only about half of the city market where safety consideration would dictate retention of curbing on heavily travelled residential streets.

Business Streets

Suburban and city businesses streets were evaluated separately because of substantial differences in design levels. The relative cost for porous and conventional design with storm sewers was \$6.38/y^2 vs. 8.40/y^2 and 7.66/y^2 vs. 18.20/y^2 for suburban and city business streets respectively. A limited demand for color infusion was evidenced for visually differentiating deceleration lanes, in which use colored surfaces would command a \$1.00/y^2 to \$1.50/y^2 premium.

Country Roads

The relative cost of porous pavement was \$6.44/y^2 compared to \$9.20/y^2 for conventional design with storm sewers. A very limited market for colored surfaces was indicated, primarily for aesthetic enhancement in scenic areas.

Highways

Substantial cost differentials were observed between porous asphaltic concrete and conventional storm-sewered pavements. The differential reflects primarily the extremely heavy expense of installing storm drains in outlying areas where interceptor systems are not available and stormwater must frequently be carried considerable distances to a discharge point. The cost of porous design was approximately half that of conventional installations for two-lane highways and only a third of conventional costs for four-lane highways. Considerable interest was expressed in the use of colored surfaces for directional routing. Based on the cost of current colored highway surfaces, the economic value of this use would range from \$2.50 to \$3.50 per square yard.

Playgrounds

The cost of porous pavement playgrounds was determined to average $\$6.34/y^2$ in contrast to $\$4.55/y^2$ for conventional installation. Again, part of the differential reflects the relatively high level of the Asphalt Institute specifications in contrast to conventional practice. Color infused surfaces were desired in most of the play surface market with commandable premiums of $\$1.00/y^2$ to $\$2.20/y^2$ depending on the type of installation.

General Economics

1. Except for very low-level design uses, the cost of porous pavement is equal to or cheaper than the cost of conventional pavement with storm or combined sewer facilities. For very high-level design roads, the cost differential in favor of porous pavement is highly significant.

2. Special ecological benefits of porous pavement - relief from combined-sewer overflow pollution and water-supply augmentation - have a potential for considerably enhancing the value of porous pavement in a relatively large proportion (roughly 20%) of the nation, by reducing the need for building more sewerage and treatment plant capacity.

3. To the extent that the use of porous pavements over large upstream areas can mitigate floods due to runoff, the costs in lives and property of such floods can be reduced.

4. While safety considerations would dictate the retention of curbing in heavy traffic areas, the elimination of curbing in suburban residential streets would effect a considerable saving of from $1.50 to $2.40 per square yard of street surface.

5. Other special benefits of porous pavement, such as preservation of vegetation, relief from flash flooding, and preservation of natural drainage patterns, would command a significant economic premium but would have a relatively limited market.

6. A broad demand for a color-infused asphaltic pavement was evidenced for three primary uses: traffic control, aesthetic enhancement and temperature control. A premium value of $0.30 to $3.30 per square yard, depending on intended use, was indicated for such a surface.

7. If a porous paving material were designed which is capable of being laid during the winter, it would command a premium exceeding $1 per square yard in the residential sector.

8. The annual cost of maintenance and surface replacement must be minimal in order for porous pavement to be a realistic alternative to conventional surfaces. With few exceptions, these maintenance costs were determined to average 2 percent or less than the cost of conventional pavement with drainage. Although, theoretically, there is an obvious economic tradeoff between initial cost and annual upkeep costs, political realities preclude this tradeoff from being effective both because of inconvenience to the public and difficulties of obtaining substantial increases in maintenance appropriations.

9. Overall pavement demand for the major uses considered was estimated at 967 million square yards annually. Of this total, the highest users, in order of their respective contribution to total demand, were low-design residential streets, county roads and parking lots.

10. Given the significantly favorable economic differential heightened by a number of special benefits, porous surfaces have the long-range potential for becoming the preferred alternative to many conventional pavement uses. This potential is, however, dependent on a convincing evaluation of the physical characteristics and maintenance experience sufficient to prove that no problems exist which would offset favorable economic indications.

SECTION II

RECOMMENDATIONS

The physical feasibility of porous asphaltic concrete has been demonstrated in the laboratory, and its economic viability has been demonstrated. Further research into porous surfaces is, however, indicated in several areas. Recommended areas of further investigation are identified below:

1. Although the physical feasibility of porous pavement has been demonstrated in the laboratory, porous pavement still needs to be evaluated under actual service conditions. A demonstration program should be undertaken to evaluate the performance of porous asphaltic concrete over time under varying soil and climate conditions. The demonstrations should be organized at sites large enough to install both a test porous pavement and a control conventional pavement for comparison, and should be located in areas where it would be possible to instrument both the conventional and test pavements. Low-Level design surfaces--residential streets, parking lots, and playgrounds--are the most feasible surfaces for such a demonstration program. The following determinations should be made in the demonstration experiments:

   a) The adequacy of porous pavement to imbibe water and avoid runoff under varying levels of rainfall.

   b) Its ability to survive weather, traffic loads, and other conditions and how its performance changes with time and season, particularly under freezing conditions and after application of de-icing compounds.

   c) The quality of imbibed waters, before and after percolation into the soil.

   d) The cleanability and maintainability of the porous surface. If the porous surface is found to clog with debris, then the efficiency, cost and machines for vacuum cleaning and other maintenance procedures will have to be evaluated.

   e) The effect of polluted water flowing through the pavement.

   f) Public reaction to the pavement in terms of its comfort, esthetics, quietness, etc.

   g) Evidence of improved safety experiences on the porous surface.

   h) Any indication that fog could form, in unusual weather, over the porous surface.

i) The likelihood that there will be any time when the pavement will be unable to accept water, and what then will happen, for example when a rain falls after the pavement is covered with ice.

2. The extent of the evidence uncovered on the polluted character of stormwater per se indicates that serious consideration should be given to means of retaining stormwater until there is sufficient capacity in the system for it to flow to treatment plants. The use of porous pavements installed over an impervious membrane offers a promising method of retaining stormwaters until treatment capacity is available. Laboratory experiments and field trials should be undertaken to verify the feasibility of this use of porous pavement.

3. Since a very broad market demand was evidenced for a colored porous pavement surface, the performance characteristics of roofing granules adhered to porous surfaces should be fully evaluated. If this material is found unsatisfactory, a research program should be undertaken to develop a durable colored porous pavement surface.

4. Various kinds of solid urban debris have the potential for forming a resevoir capacity under porous asphaltic concrete. Further investigation of these materials is required to establish their physical suitability and determine whether water can pass through them without being polluted.

5. There are potential economic tradeoffs between reduced size of collection systems and porous surfaces, such as using a porous surface which can handle 3 inches/hour of rain and a collection system to handle the rare remainder. The economics of these tradeoffs need investigation.

6. A study remains to be made to elucidate the economic benefits of using porous pavements as a potential means for reducing the capacity of and flows to storm and combined sewer overflow treatment facilities (to be required in the near future). The savings due to the reduced cost of smaller treatment facilities and reduced operational and maintenance costs should be delineated.

7. The use of porous Portland cement concrete pavement of the type tested would not be feasible where there is shifting of the subsoil and base. Further work would be required to determine whether a gravel course lightly bonded with asphalt would have the requisite stability over an otherwise unstable soil.

8. A substantial demand was indicated for a durable, resilient, nonabrasive porous surface for playground use, if such a surface could be made available at a cost not exceeding $5 to $6 per square yard. Further exploration of available materials should be undertaken to determine whether such a porous surface can be produced in this price range. Reclaimed rubber in particular, should be analyzed as a possible material from which to achieve such a surface.

9. There is some indication that snow or ice melts faster than normal on porous pavement. Possibilities to enhance this characteristic should be explored both to reduce the impact of snow and ice on traffic flow and safety, and also to minimize the need for deicing salts. Conversely the effects if any of deicing compounds on the pavement structure and on buried structures (phone cables, water mains, etc.) as well as the effects on soil bacteria and ground water quality should be studied unless the use of salts can be dispensed with.

10. In some paving applications (bridge decks and advance base air fields, for instance), it might be advantageous to prefabricate the porous pavement, transport it as slabs, and drop it into place. Asphalt concrete would not be suitable for this, and if required, other types of porous pavement, though more expensive, should be developed for such applications.

11. Simple how-to-do-it instructions should be prepared and tests designated whereby porous pavements can be designed for given climate and soil conditions. A manual for this purpose would show also how to predict the hydrological performances of a given design in a specific situation.

Since friction coefficients, drainage slopes, inlets, drains, etc. may not be the same for porous pavements as for conventional pavements, new road and highway specifications for these purposes must be formulated.

12. Oil spills on a pavement are possible and their effects on a porous pavement system should be determined under service conditions.

13. More extensive tests than those carried out in this project will be required to prove conclusively that cleansing bacteria in the soil are unaffected by the presence of porous pavement over them. Present results are encouraging but not conclusive. These tests might best be run on outdoor demonstration pavements subjected to polluted runoff waters.

14. In view of the economic advantage of being able to lay a pavement all year round, tests should be conducted to determine whether there are any unusual problems in laying the porous asphalt concrete in winter.

15. Noises are generated by skidding of tires on pavement and the rolling of tires on pavement; ambient noises are reflected or absorbed by pavements. How porous pavements compare with normal ones in their effect on noise levels is largely unknown, and, in view of the increasing interest in noise pollution, should be measured. Tire squeal due to skidding, and reflection of ambient noises should be reduced; rolling friction noises levels from porous pavements need to be determined.

16. A considerable technology exists for the selection of asphalt grades for specific applications, and for the improvement of asphalts by additions of rubbers, resins, fillers, and fibres. The performances

in service of open-graded asphalt concrete pavings should be further surveyed and studied and guidelines prepared for selecting the optimum asphalt grade and admixture, it required, for each application.

It is likely that this formulation wave will produce an asphalt concrete with considerably greater strength and resistance to creep than the ones studied. If this can be achieved low design pavements may not require a full four inches of opengraded asphalt concrete and some economics may result.

17. When gravel is laid directly on a soil which is very soft when wet, the gravel tends to sink into the soil, and become clogged by it. To avoid this, a layer of sand or of filtering fibres (such as a thick fibre glass felt is often placed between the soil and the gravel. Research should be carried out to determine under what conditions such a layer would be advantageous in the porous pavement system.

SECTION III

INTRODUCTION

A proposal dated August 13, 1969 was submitted to the Office of Research and Monitoring Environmental Protection Agency, to develop porous pavements; to determine their feasibility for a number of applications and to build and test sample areas for demonstration purposes. The proposal was accepted and work was initiated in Phase A on October 30, 1970 by The Franklin Institute Research Laboratories.

The porous pavements were intended:

1) To absorb rain where it falls, preventing runoff and overflows from combined sewers and treatment plants required to handle stormwater loads.

2) To hold back stormwater surges to increase the capabilities of existing facilities to handle them.

3) To allow the filtered water to percolate at its own rate into the ground, and/or to store it for use;

4) To mitigate vehicular accidents and to minimize personal injuries on playgrounds.

5) To avoid puddles in flat surfaces (such as parking lots) and provide adequate drainage without crowns and vertical contouring.

6) To conserve water and land;

7) To present a satisfying appearance;

8) To minimize damage to the ecology, and

9) To provide a possible means of disposing of certain solid wastes.

This study was visualized in three phases. Phase A is a feasibility study related to technological and cost capabilities of several types of porous pavements. Phase A includes application requirements over several types of soil, benefits to be achieved by avoiding runoff, and acceptability, of the paving to governmental bodies, contractors, and other interested groups.

This report covers results obtained under Phase A.

The bulk of the work consisted in studying and developing the most potentially useful type of porous pavement, and in determining the economic feasibility of porous pavements in general and this one in particular.

The purpose of Phase B was to select and obtain test areas in which the most promising designs for two or more applications could be put to practical test.

Phase C was to establish a test regimen for instrumenting and monitoring the demonstration areas to evaluate the performance of the prototype porous pavement and to compare it with conventional pavement.

SECTION IV

POROUS PAVEMENT DESIGN

1. Applications

Table 2 lists 10 representative pavement applications, and includes the loads, speeds, and frequencies of traverse estimated for the traffic on each. Also included are Special Considerations which are discussed in more detail in the next section of this Discussion.

Estimated maximum loads are based upon the weight or pressure of the vehicle or person, the size of its "footprints" and the spacing between them. Looking at item 4 in Table 1, a tire inflated to 60 psi has a contact area of less than one square foot and might support up to 2000 lbs. of vehicle. However there is likely to be only one wheel on a square yard of paving, hence the load per square yard also is listed as 2000 lbs.

The first three applications deal with human traffic and the next two with passenger vehicle and light truck traffic. Three more include heavy truck loads and the last two deal with airport traffic in terms of the biggest aircraft in operation, the C-5A.

The first five applications are subjected to relative low traffic loads, hence are more feasible than the others at sites where the soil when wet may be quite poor in load bearing capacity.

Among the design features planned with porous pavement for many applications and locations are the following:

a) It shall carry the loads without damage.

b) It shall imbibe all or most of the rainfall on it, and water from melted snow and ice.

c) It shall survive freeze-thaw and weathering; long life is required.

d) It shall be hard to damage but easy to repair; maintenance cost must be moderate.

e) It shall not plug up; removal of trash by occasional sweeping or vacuuming may be permissible.

2. Water Flow Delay or Storage

A built-in reservoir capacity shall be designed to provide the following:

Table 2

APPLICATIONS

Pavement Applications	Estimated Loads Maximum (1) Pounds per square inch	foot	yard	Speed High-Average mph	Frequency Passages per minute	Special Consideration
1. Sidewalk	30	300	900	6	10	Appearance
2. Public Square	30	300	1,500	4	20	Appearance
3. Playground	25	250	750	8	20	Resilience-injury
4. Parking Lot	60	2,000	2,000	10	5	Shopping carts, color
5. Residential Street (restricted traffic)	40	1,200	1,600	30	10	Plantings alongside, color
6. Service Road	90	7,000	15,000	15	5	Litter
7. Business Street	70	5,000	10,000	30	10	Traffic Stripes
8. Highway	90	7,000	15,000	65	26	Wet Skid
9. Taxi Apron (2)	200	28,000	60,000	6	3	Fuel and oil spills
10. Airport Landing (2)	200	28,000	60,000	300	3	Wet skid and hydroplaning

(1) Not including impact.
(2) C-5A Transport

a) Depending on the permeability and drainage of the underlying soil, its percolation rate may be less than the rate of rainfall; the pavement will store the incident rain and provide time for its slow percolation.

b) Similarly, the water collected within the pavement would take some time to drain out, hence could be fed slowly to a combined sewer avoiding present peak loadings, and/or reducing the required size of a storm sewer.

c) Alternatively, with an impervious membrane under the pavement the water can be collected in the reservoir layer from which it can be pumped, using a sump and pump, for irrigation or other purposes.

3. Water Treatment

Two provisions for water treatment shall be incorporated:

a) The water will be filtered as it passes through the pavement, the sub-base and the subgrade.

b) Aerobic bacteria should be able to survive under the pavement and help to destroy organic contamination that could clog the soil or pollute the water.

4. Accident Mitigation

Safety features of the new pavement shall be developed:

a) By mitigating street water from the pavement surface during storms, the incidence of accidents due to hydroplaning and loss of friction by vehicles will be greatly reduced.

b) By laying the pavement flat and eliminating gutters and crowns, control of the vehicles, particularly at intersections, will be improved. Since puddles will drain into the pavement, it does not have to be crowned.

c) It may be feasible to impart to the pavement a surface texture or configuration that will help to prevent skidding, not only of vehicles but also of people on playgrounds and sidewalks.

d) A light color will be incorporated when desired to improve visibility and safety.

e) For playgrounds, a non-abrasive resilient surface will be sought, which together with the elimination of puddles, will reduce accidents.

5. Appearance

From an esthetic point of view, this feature is of interest:

a) Elimination of gutters and crowns means the pavement can be level with the parking area from a consideration of runoff; this, together with lighter colors, should make a more attractive road, particularly in residential areas and parks.

b) Elimination of drainage ditches for unsewered roads should make them safer and more attractive.

6. Ecology

In terms of ecology and environment, Mr. Richard James, Director of the Schuylkill Valley Nature Center, raises these points:

a) Plants and vegetation along conventional roads often are starved for water because the dry soil under the roads tends to rob their supply. Water falling on most pavements, if not collected in gutters, tends to cause erosion of the bordering soil. These difficulties would not occur with porous pavements.

b) The heated air from large expanses of dark asphalt paving are suspected by metorologists of causing thunderheads to develop on summer afternoons. This may cause moisture-laden air to dump its water on the cities where it loads the storm sewers, rather than carrying it over to the farm lands beyond. A light-colored pavement should not have this effect.

7. Solid Waste Disposal

A useful goal, which was identified in a discussion with Mr. Rosenkranz and is seen to be feasible, is as follows:

If a reservoir is to be created under the pavement, this could be a place to deposit broken bricks, ceramic wastes, solidified fly ash and other bothersome solid residues of the cities. However, materials to be disposed of in this way will have to be known to be non-polluting of the water passing through them.

8. Paving Design: Technical Constraints

All pavement designs in the end depend upon subgrade support to prevent undue deformation and roughness or break-up of the pavement.

Additionally the pavement surface itself has to be durable to traffic and weather. In the usual pavement design the pavement rests upon a base, and possibly a subbase which in turn is on compacted subgrade. A base usually is required since only rarely does the compacted subgrade have sufficient supporting value and resistance to water and frost conditions.

Rigid pavements, such as the Portland cement concrete type, depend in design upon beam support, but at high stress locations such as at the corner areas near joints they also can require localized subgrade and base support. Flexible pavements, the asphalt binder type, depend upon localized support, although with full depth design in which the base also is bonded with asphalt, they more nearly approach the rigid type in beam supporting value under dynamic loading.

The usual pavement design prevents or attempts to prevent water from entering the base and subgrade. Otherwise water seeping or flowing through the pavement surface lowers the supporting value of most subgrades, and thus would require increased depth of the base structure. If water is to penetrate through the base, the compacted subgrade and the earth underneath, the problems will be to provide the required drainage rate and/or water storage capacity; to obtain the necessary minimum supporting bearing value of the subgrade; and to generate sufficient frost resistance. Otherwise the pavement will have an unsatisfactory economical life under its present and future expected traffic.

The theoretical approach to porous pavement design thus requires that a pavement have the required permeability to water, be durable in age under traffic, be adequately supported by the base and subgrade under conditions of water saturation and that the overall design be economical. An additional consideration is that particulate organic matter flushed through the pavement voids be decomposed by bacterial action, lest plugging of the subgrade occur.

9. Factor Fabricated Paving Structures

Two general categories of porous pavements were considered:

a) Those fabricated in a factory and delivered to the site for assembly and installation, and

b) Those delivered as bulk materials to the site and there spread and compacted into place.

Factory-fabricated structures can be precisely shaped and sophisticated in design, and materials can be specified within relatively narrow limits.

Four examples of these were studied:

The Portland cement concrete structures, special brick and honeycomb structures, Astroturf rugs, and various products studied for playgrounds as described in Section XIII.

The one bulk material that was found suitable is open-graded asphalt concrete. When its feasibility became evident, the factory-fabricated materials, by comparison, were seen to be uneconomical.

All of the factory fabricated pavements have higher materials costs than open-graded asphalt concrete. They require labor at the site to assemble and install them, whereas the asphalt concrete can be mixed in existing paving plants and laid with a Barber Greene type machine and rolled with standard equipment.

Factory fabricated porous pavements might have utility for emergency or military airstrips and for roads that have to be installed in a minimum of time. They could also be useful for bridge decks or other structures not laid on soil.

In view of the very minor impact of such limited applications on run-off and sewage problems, they were not investigated further.

SECTION V

DESIGN OF HOT-MIX ASPHALTIC CEMENT PAVEMENTS

In terms of cost and practicality, the porous pavement should be made from conventional paving materials, and applied at the site by conventional pavement-laying devices. An open-graded hot mix asphalt concrete, alone of all the materials considered, meets these requirements.

Several specifications of open graded asphalt concrete pavements have been promulgated by various agencies; generally these pavements are used either to avoid wet skidding or hydroplaning accidents, or as a revetment, to protect dam faces, or other embankments. (Ref. 2).

For the safety application, the material is laid 3/4" to 1" thick over a normal dense pavement. Water drains laterally through this course, to its edges. Applications of this sort have been used successfully for 25 years in California, which attests to their mechanical and photo-oxidative durability (Refs. 1 and 6).

A dense concrete runway was overlaid with an open-graded asphalt concrete course on a runway at the British Royal Air Force Farnborough Airport in England. It successfully withstood multiple landings of aircraft with 12,500 pounds force wheels loadings, and has survived several years of weathering (Refs. 3 and 5). It is claimed that open-graded asphalt concrete pavement provides better protection against wet skidding and hydroplaning than is afforded by grooving the pavement.

Other sgencies trying out asphalt concrete porous pavement for safety reasons are the U.S. Air Force at Albuquerque, New Mexico, the States of Louisiana, Colorado and Pennsylvania, etc. The widespread interest in this material should cause it to be commercially available also for water conservation purposes.

Asphaltic base pavements, primarily prepared with asphaltic cement binders can be made with a variety of asphaltic products, as cutbacks and emulsions. This investigation, however, was concerned only with the use of asphaltic cement binders since until the cutbacks and emulsions become thoroughly set, the water stripping tendency would be great in porous asphaltic pavements. As defined herein porous asphaltic concrete is a graded aggregate cemented together by asphalt cement into a coherent mass, with sufficient interconnected voids to show a high permeability to liquid water. [The maximum intensity of rainfall expected in the United States for a duration of one hour from a storm that might occur once in 50 years is 5 inches per hour (Pennsylvania = 2.2 to 2.8 inches/hr). For a 10 year period it is 4 inches per hour (Pennsylvania = 1.6-2.2 inches/hr).] In manufacture, the graded aggregate is dried by heating to 275°-300°F, and mixed with hot asphalt cement. The hot-mix material is hauled to the paving site, where it is applied in a spreading machine in smooth layers, and compacted to design density by heavy rollers.

Properties required in porous asphaltic concrete pavement are:

It should be durable and not deteriorate under weather or traffic.

It should be economical and not employ expensive materials.

It should be safe under traffic. As will be discussed later, porous asphaltic concrete has exceptional skid resistance properties.

The following factors are primary in design of porous asphaltic concrete pavement:

1) Aggregate Gradation

The gradation required to obtain a porous asphaltic concrete pavement is of the "open" graded type as contrasted to the "dense" graded type which is capable of close packing.

2) Type and Quality of Aggregate

The aggregates selected for porous pavement construction should meet the requirements of the standard specification for "Crushed Stone, Crushed Slag, and Crushed Gravel for Bituminous Macadam base and Surface Courses of Pavements", ASTM C-693-71, with one exception and one addition. The exception is in requiring the gradation to be of the open graded type of the reasons described below. The addition should be a requirement for a soundness test as specified in ASTM D-694-62, "Crushed Stone, Crushed Slag, and Crushed Gravel for Dry-Bound or Water-Bound Macadam Base Courses." This is required to determine if the aggregate is susceptible to disintegration by water.

3) Asphalt Cement Grade and Content in Mix

Possible factors in open graded mixes because of their relatively high permeability to air and water are their durability to freeze-thaw and to asphalt film oxidation. To offset this, experience has shown that a minimum asphalt content of 5.5% by weight in the mix with a relatively soft asphalt can provide a very satisfactory service life. Suitable asphalts have penetrations of 85 to 100 dmm, ASTM D-5.

A requirement commonly specified for mixes and of special importance in water permeable mixes is set forth in "Coating and Stripping of Bitumen-Aggregate Mixtures", ASTM D 1664. The asphalt coated aggregate should retain an estimated 95 percent of the coated area after water immersion of the mix for 16 to 18 hours at 77°F. (25°C).

Mix and pavement thickness design methods for conventional pavements are quite standardized and are given by publications of the Asphalt Institute. Porous pavement design differs in that the so-termed open aggregate gradation is selected as opposed to the usual dense gradation. The desired gradation as determined by this investigation is discussed under the section, "Surface Course." The design requires that the surface course have the required stability to traffic to not be displaced by traffic loading, either by rutting or raveling or shoving.

Overall thickness design of porous asphaltic concrete pavements is determined by a number of factors, viz:

1) Subgrade supporting value in a wet compacted condition. This determines the depth required of both the base, sub-base, and surface course. The California Bearing Ratio (CBR) technique commonly is used to measure the load bearing characteristics of the subgrade soil. The test consists of measuring the load required to cause a plunger of standard size to penetrate a soil specimen at a specified rate. The CBR is the load in pounds per square inch, required to force a piston into the soil a certain depth, expressed as a percentage of the load in pounds per square inch, required to force the piston the same depth into a standard sample of crushed stone. Usually depths of 0.1 inch or 0.2 inch are used. Penetation loads for the crushed stone have been standardized. The resulting ratio of bearing values is known as the California Bearing Ratio.

2) Water storage capacity. Subgrades, that is the existing soil structure, vary greatly in their capacity to infiltrate water. With soils showing low infiltration rates, the base thickness may need to be increased to have sufficient storage capacity to permit the rainfall to infiltrate in a reasonable time, herein arbitrarily selected as 10 days. With some soils, as clays and fine silts, the infiltration rate may be so low that other means may be required to introduce the water into the earth, as infiltration pounds or sand drains. Such soils, however, do not make suitable subgrades and usually it is more economical to replace them with selected borrow with better support value. Such replacement also would have the advantage of having a higher storage capacity and infiltration rate.

3) Frost penetration. If the climate is such that frost will penetrate deeper than the anticipated thickness of surface and base and the subgrade is susceptible to frost heaving, additional subbase will be required. Frost penetration in inches has been related to an air freezing index. Charts of these freeze indices and frost penetrations are available in standard publications as, Asphalt Institute "Drainage of Asphalt Pavement Structures", MS-15 (1966).

On an average, for one year in ten, values for frost penetration in the eastern United States vary from 12 inches in Northern Tennessee to around 100 inches in middle Maine. Acceptable soils to resist frost heaving have been defined by a triangular chart, Asphalt

Institute publication MS-15 (1966), with essentially the clay and silt contents of the subgrade to total less than 40% by weight.

4) Design Traffic Number. An asphalt pavement structure deflects downward under a moving load, and returns almost to its original position after the load has passed. This "almost" is important, since under continued traffic the permanent deflections add to altered pavement profiles, and may possibly result in pavement cracking. By taking into account the anticipated traffic the base thickness may be increased to reduce the deflection of the subgrade under traffic load to an acceptable value.

The anticipated traffic is calculated as a Design Traffic Number (DNT), which is the average number of equivalent 18,000 pound single axle loads per day expected in the heaviest traffic lane during the design period (normally 20 years). The method of calculating the DNT is given in detail in the Asphalt Institute Manual Series No. 1, "Thickness Design," the classifications of traffic are as follows:

DTN	Traffic Classification
1-10	Light (Parking lots, residential streets)
10-100	Medium (City business streets)
100-10,000	Heavy (Highways)

SECTION VI

ASPHALT PAVEMENT STRUCTURES

a. Surface Course

Asphalt paving mixes may be designed and produced from a wide range of aggregate blends, each suited to specific uses. The aggregate composition may vary from course to fine particles. To sort out the differences in grading, porous asphalt paving mixes have been classified into three types according to their water infiltration rates, 1) less than 5"/hr, 2) 5"/hr to 25"/hr and 3) greater than 25"/hr. The Asphalt Institute, British and California gradations shown in the experimental phase of this report represent types 1, 2 and 3 respectively. The permeabilities and seepage rates also vary considerably with changes in asphalt content.

The Marshall test procedures for designing paving mixtures give the guidelines for preparing a mix capable of withstanding different traffic conditions. The criteria are in Table 3.

Table 3

MARSHALL DESIGN CRITERIA

Traffic Category	Heavy		Medium		Light	
No. of Compaction Blows (each end of specimen)	75		50		50	
Test Property	Min.	Max.	Min.	Max.	Min.	Max.
Stability (lbs)	750	-	500		500	
Flow (.01 inch)	8	16	8	18	8	20
% Air voids	3	5	3	5	3	5

As the experimental data of this program will show, stability and flow requirements obtained were more than adequate for each of the three types of our classification. The % Air voids, however, which are mentioned in the Marshall Criteria are not appropriate for a porous surface course. The Asphalt Institute gradation gave values as high as 8.2% air voids but provided a seepage rate of only 1.15 in/hr. This would be adequate only for minimal rainfall conditions. Seepage rates generally required can be adequately provided by both the British and California aggregate gradations specification for a porous concrete at asphalt concentration of 4.0% for the British and 4.0 to 5.5 for the California. For purposes of road paving durability to prevent too rapid a hardening of the asphalt it is desirable to have the highest asphalt content possible in the mix. Too much asphalt would separate out under traffic and hence maximum asphalt content would be limited by this factor. 5.5% asphalt content with the California aggregate specification would appear to be the optimum.

If we take the Asphalt Institute's recommendation of a 4" minimum surface course we obtain a 0.60" rainfall reservoir capacity within the surface course with the 5.5% California specification and a seepage rate of 176 in./hr. This was the maximum obtainable. The combination of the surface course with the base course enhance total rainfall hold capacity as will be shown later.

b. Base Course

Asphalt pavement structures must be designed and built to support the heaviest traffic volumes and loads for a particular application. By increasing the depth of the base course, loads are spread conically over large areas, thus reducing the loading intensity until the subgrade will support the load without undue deformation.

A porous asphalt pavement structure must not only carry the loads without damage but must also:

1. Imbibe all or most of the rainfall on it, and water from melted snow.

2. Survive freeze-thaw and weathering.

The base course depth can and will provide for the load and act as a water reservoir.

The base course generally consists of crushed gravel. It is used under the surface course to distribute loads, store water and prevent freeze-thaw problems. In place of gravel, broken bricks, ceramic shards or other urban solid wastes or suitable strength and insolubility might be disposed of here. For relatively uniform-sized lumps, a void volume of 38 to 46% might be expected. If a 40% void volume is assumed the average, a twelve-inch layer would hold 4.8 inches of rainfall.

c. Subgrade

Water continually in contact with silty or clay types of subgrade soils will saturate and decrease the strength of the subgrade and, in turn, lower the load-carrying capability of the roadway. Therefore an ideal soil for use as a subgrade must have adequate load-bearing capacity wet and dry. This ideal soil must be well drained that is, the water table is so far below the surface that the rise of water by capillary action will not come close to the surface. It must be permeable to water, so water is transmitted relatively quickly down through it. Finally, it must be quite porous so it has the capacity to inbibe large quantities of water in its surface layers.

A likely soil to meet these requirements would be a sandy silt some distance above the water table. The coefficient of permeability for such a soil must be greater than .01 ft/day if a full reservoir is to be emptied within a reasonable amount to time. The particle for this type soil ranges from sand to clay, but the clay content is low enough to leave good void volume and permit capillary flow downward at a suitable rate. If highly sandy a low content of asphalt often is added to improve interlocking of the sand particles and improve load bearing properties of the soil; good transmission characteristics will remain satisfactory. If it is too clayey, the soil compacts very well and carries the load when dry, but porosity is lacking and transmission of water through the clay is very slow. Clays may also absorb more than enough water to fill their voids, thereby swelling and becoming very low in load support value.

It is possible to treat a high clay soil with lime or cement to aggregate the grains, making it more porous and less likely to be swollen by water. Such soil treatments have been developed over the years, and can be considered when the top layer of soil is deficient. If the underlying soil lacks permeability, however, treatment of the top layer would not correct the problem.

d. The Porous Asphalt Pavement Structure

In designing the total structure for use as a porous pavement without the use of membranes or drains it is necessary to ascertain the following:

1. Design traffic number (DTN).
2. Load bearing capacity of the wet subgrade (CBR) and its permeability.
3. Permeability, strength, flow, and durability of the surface course.

The Asphalt Institute recommends that a minimum of 4 inch surface thickness be used regardless of the DTN. Using this as a basis, Table 4 was compiled for a low load bearing ratio and varying DTN's

Table 4

REQUIREMENTS FOR SURFACE AND BASE COURSE STRUCTURE

CBR	DTN	Thickness (in.)	Surface Reservoir Capacity (in. Rainfall)	Base Thickness (in.)	Base Reservoir Capacity (in. Rainfall)
2	1	4	.60	6	2.40
2	10	4	.60	12	4.80
2	20	4-1/2	.66	13	5.20
2	50	5	.75	14	5.60
2	100	5	.75	16	6.40
2	1000	6	.90	20	8.00
2	5000	7	1.05	22	8.88

The reservoir capacity for the surface and base courses are based on 15 and 30% air voids respectively. These are conservative.

If we assume that the load bearing capacity of the subgrade is poor (CBR = 2) when wet and we wish to design a pavement structure for a residential street (DTN = 10) in an area where we might expect a 5" rainfall in a 24 hour period, we can see from the Table that a 4 inch surface course and a 12 inch base course would be adequate to handle both the traffic and rainfall. On the other hand, if the DTN is one and the rainfall expected is still 5"/day, then we must still use the 4" and 12" surface and base course thicknesses.

Once the reservoir is filled it must be emptied by percolation through the subgrade. Figure 1 shows the permeability of subgrade soil required to empty the reservoir within a reasonable amount of time. If, for example, we wish to remove a 5" rainfall from the reservoir in ten days, the subgrade soil must have a permeability value of at least .042 ft/day. This value would be typical of a fine sand and silty soil.

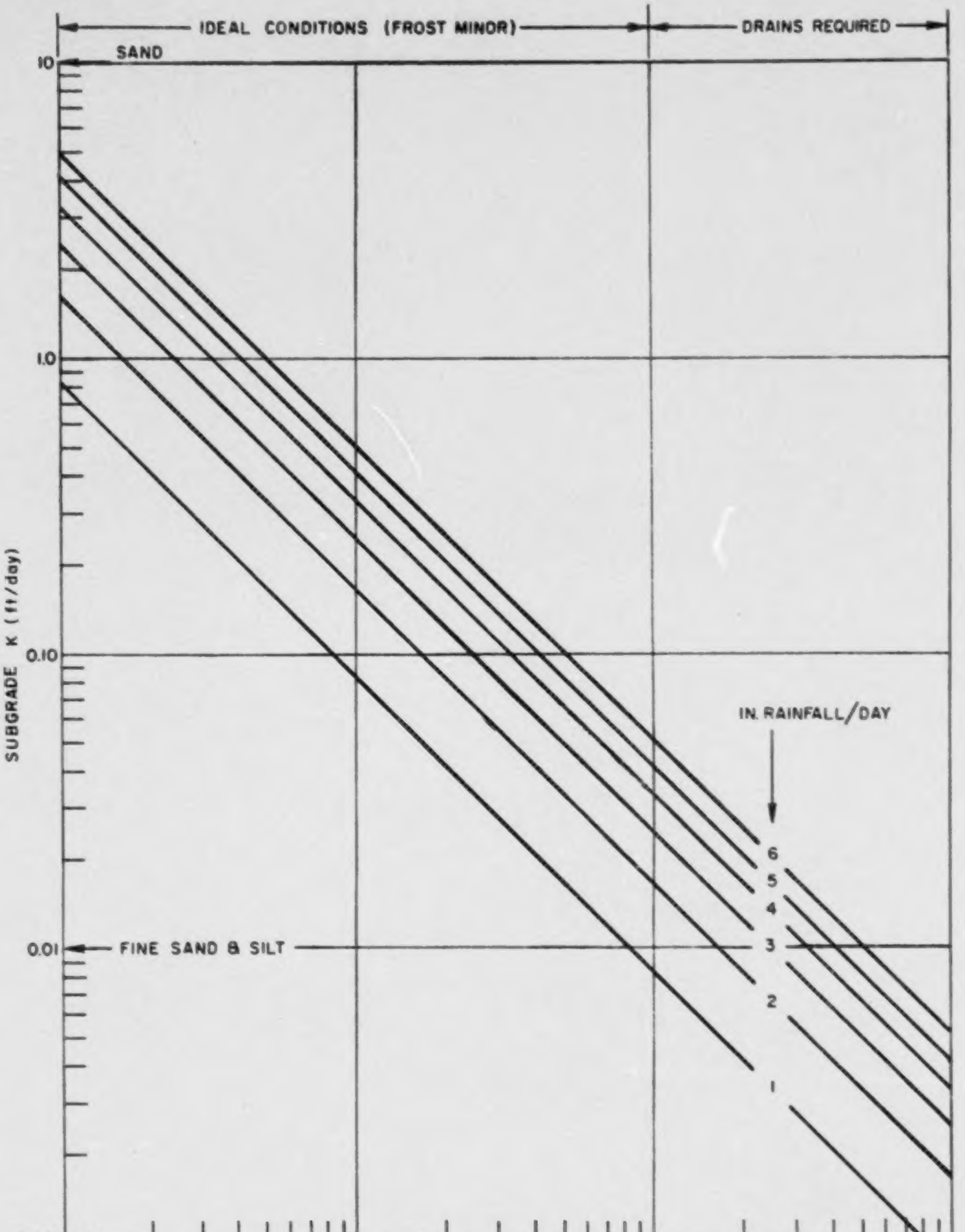

Figure 1. Subgrade Soil Permeability Requirements

SECTION VII

MATERIALS AND METHODS PHASE

The materials necessary to construct a porous asphalt concrete top surface course consist of (1) appropriate penetration grade asphalt and (2) properly sized crushed aggregate. It was decided early in the program to use 85/100 penetration grade asphalt (ASTM procedure D-5) as a standard since it is in wide use today on the nation's highways. This material has shown good strength and durability properties over the years of its use. The crushed aggregate in our experiments was comprised of two different aggregates, a coarse and fine graded crushed limestone and sand.

The hot-mix asphalt paving mix is a combination of crushed aggregates uniformly mixed and coated with asphalt cement. The porosity of this mix is dependent upon the gradation of the aggregate portion, the amount of asphalt used as the binder and the degree of compaction. The aggregates must be dried and the asphalt cement be sufficiently fluid for proper mixing and workability. This necessitates that both the aggregate and asphalt be heated sufficiently prior to mixing. It is also required that heating be continued or that as little heat as possible be lost during mixing and compacting.

a. Marshall Method

A procedure in wide use today for both laboratory design and field control of the asphaltic load bearing properties of hot-mix paving is the Marshall Method. It is applicable to hot-mix paving mixtures using penetration grades of asphalt cement containing maximum particle sizes of one inch or less in the aggregates. This method has been standardized by the American Society for Testing and Materials, as given by ASTM designation D-1559, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus." The procedure consists basically of preparing hot mix asphalt concrete samples in 4" dia. by 2-1/2" high molds, maintaining the proper temperatures to keep aggregate dry and the asphalt fluid enough to be mixed uniformly in a mechanical mixer. The uniform mix is compacted in the molds with a 10 lb hammer being dropped a distance of 18" on first one side of the specimen and then on the other; 35, 50, or 75 blows can be applied to each side depending on the traffic category for the mix. This procedure was used throughout the course of the project with certain exceptions as presently will be noted.

b. Permeability

Since the program was concerned with porous asphalt mixes a permeability test was developed based on the Marshall specimens. By this procedure Marshall samples could be tested prior to being extracted from their molds. A compacted specimen while still in the mold is bonded tightly at the walls of the retaining structure and thus wall leakage problems are eliminated in the permeability

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apparatus. The ASTM designation D-2434 method for measuring the permeability of compacted soil was modified and utilized for this work. The general arrangement of this apparatus is shown in Figure 2. A constant head water bath supplies water flow through the specimen, after it has been evacuated with an aspirator for 15 minutes. The hydraulic gradient across the specimen is measured with manometer openings placed directly above and below the specimen. Test runs were conducted by varying the head pressure in 1/16" increments to establish a region of laminar flow through the specimen. This condition is necessary for application of Darcy's law which measures permeability. Basically, it states that the velocity of a liquid through the specimen is directly proportional to the hydraulic gradient across it. From this relation it is possible to compute the coefficient of permeability (K in ft/day) for the specimen as follows:

$$K = \frac{QL}{Ath}$$

where

K = Coefficient of permeability (ft/day)
Q = Quantity of water discharged (Cu ft)
L = Distance between manometers (specimen height) (ft)
A = Cross-sectional area of specimen (Sq ft)
t = Total time of discharge (days)
h = Difference in head on manometers (ft)

c. Freeze-Thaw

The permeability apparatus also was used to aspirate samples prepared for freeze-thaw tests. The 4" dia. by 2-1/2" high samples were made using the Marshall Method. These samples were drilled halfway through, to their centers, for housing a thermocouple well consisting of a 1/4" diameter by 1/4" long stainless steel sheath attached to a bakelite head. This well prevented erroneous readings of air temperature which might be read while the sample was in the freezer. A thermocouple readout system was used for measuring the sample's temperature. The following freeze-thaw cycle was used:

1. Aspirate (5 minutes)
2. Soak (15 minutes)
3. Drain (15 minutes)
4. Freeze (30 minutes) time required to bring center of specimen to 0°F
5. Thaw (30 minutes) time required to bring center of specimen to 50°F
6. Repeat

Control specimens (no water soaking) were also run.

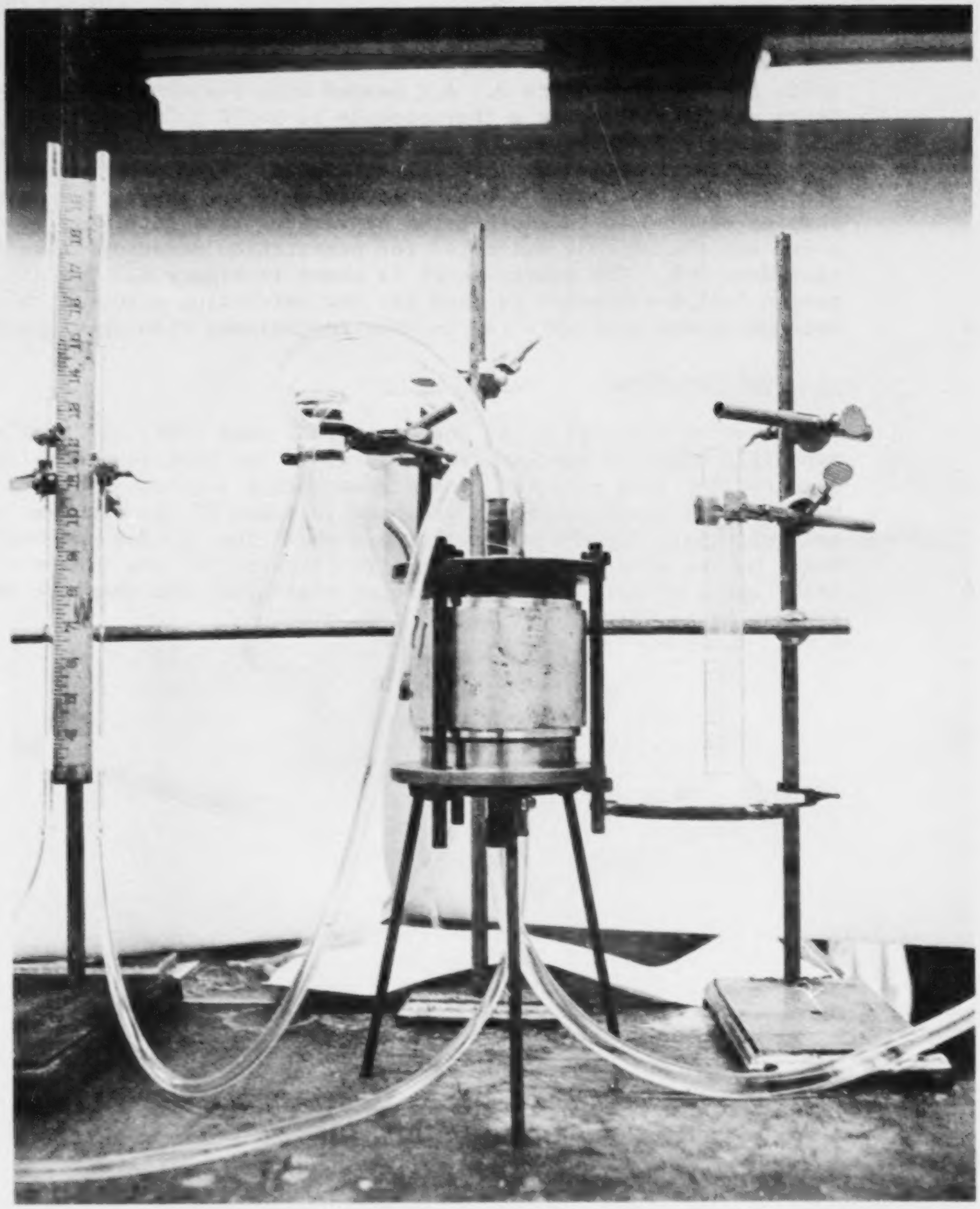


Figure 2. General View of the Permeability Apparatus

d. Durability

Since the porous asphalt concrete will allow sufficient quantities of air and water to pass through it was necessary to measure the durability to air oxidation of such a mix. A durability apparatus was constructed to house samples still in their Marshall compaction molds as shown in Figure 3. Air heated with electrical heating elements and controlled by a thermocouple to 140°F ±5°F was passed into the manifold chamber housing which can hold up to 12, 4" diameter x 2-1/2" length samples. The pressure head was maintained at 5" water head through the use of the bleeder valve in the end of the chamber. Samples exposed in this apparatus at various time intervals were removed and the asphalt extracted for penetration measurement using ASTM procedure D-5. The penetrometer is shown in Figure 4. The ASTM designation D-1856 procedure is used for the extraction process. Blank determinations also were run to make comparisons with aged specimens.

e. Tank Specimens

For covering the surface of the biological test tank, 40" x 52" in area, asphaltic concrete blocks were prepared in one foot square molds constructed for this purpose. The mix procedure utilizes the Marshall Method but a hydraulic press was used in place of the standard compaction hammer for the compaction process. The two and one-half inch thick by one square foot samples were prepared in this manner and were laid over a prepared soil bed for the biological and chemical test program to be carried out in the test tank.

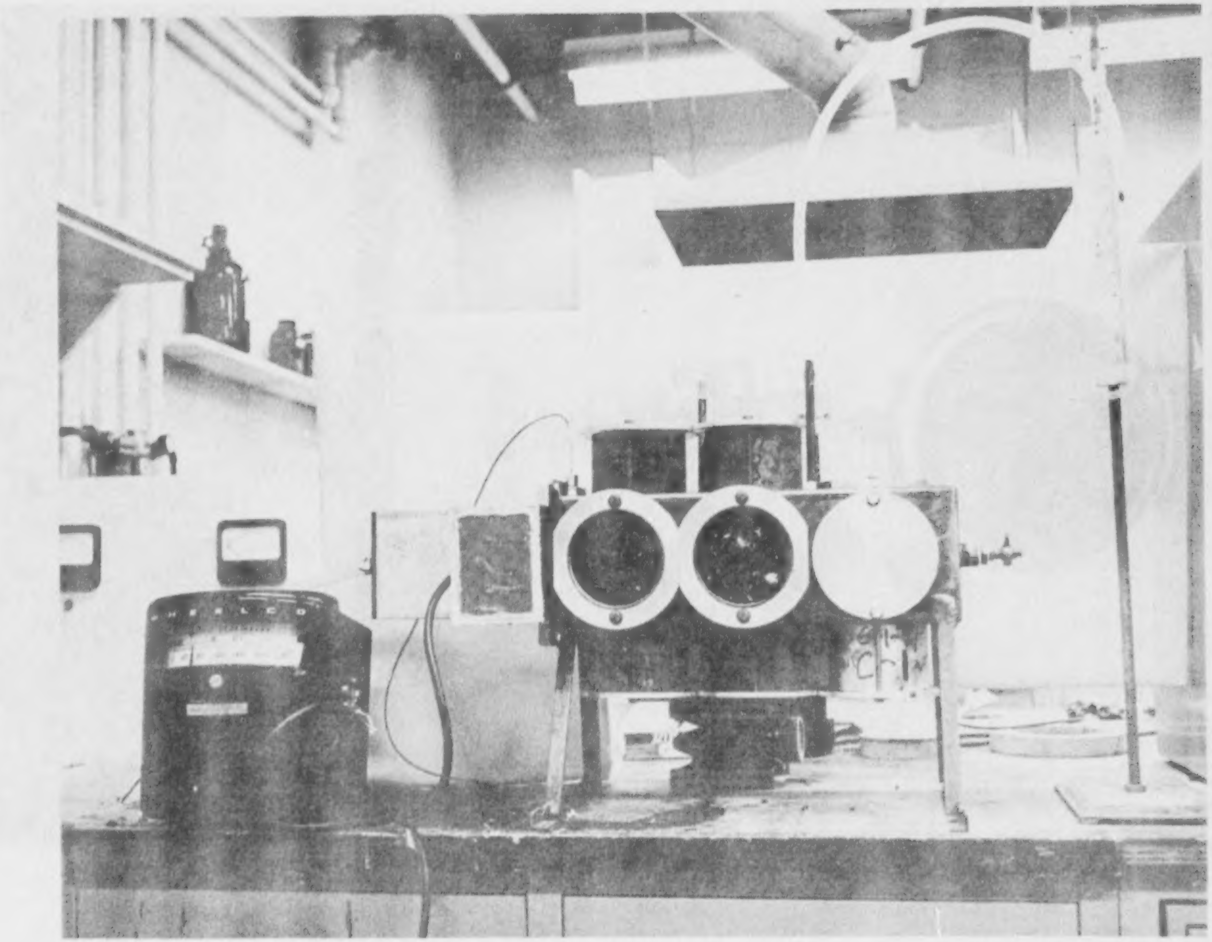


Figure 3. General View of the Durability Apparatus

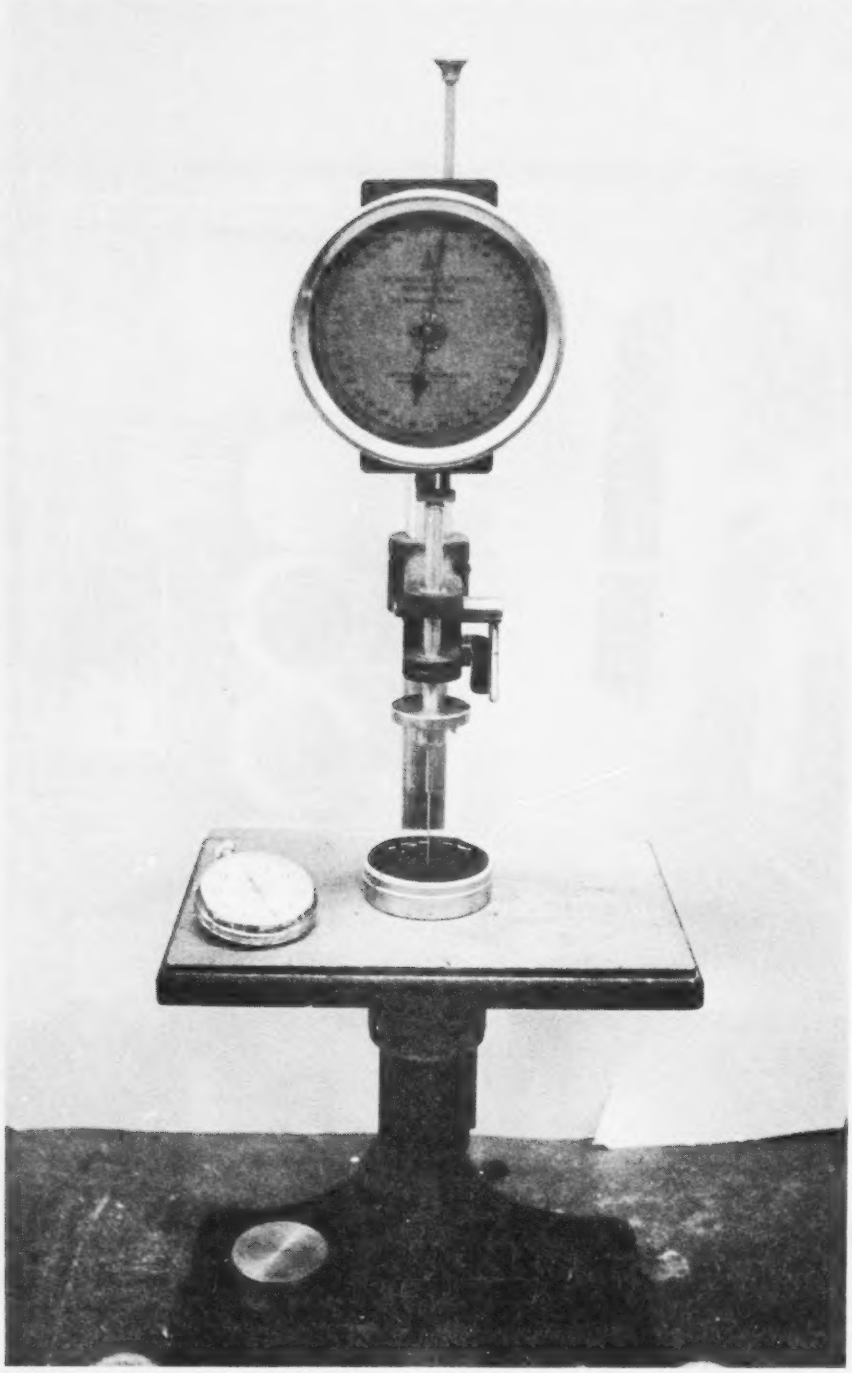


Figure 4. Penetrometer

SECTION VIII

EXPERIMENTAL PHASE

a. Aggregate Gradation

During the course of this program it was discovered that three aggregate gradations previously had been established for producing a porous asphalt concrete mix. The maximum aggregate particle sizes for all three did not exceed one inch and asphaltic mixes containing them hence could readily be tested by the Marshall Method. Their specifications (see Ref. 1, 2, 3) and the results of our (FIRL) blend were as follows:

Table 5

AGGREGATE GRADATIONS

% Passing Thru Sieve

Sieve	Opening (mm)	Asphalt Institute	FIRL	British	FIRL	California	FIRL
1"	25.4	100	100	100	100		
3/4"	19.0	95-100	98	90-100	92		
1/2"	12.7	85-95	93	60-75	76	100	100
3/8"	9.51					90-100	97
#4	4.76	44-56	47	25-35	26	35-50	34
#8	2.38			12-18	19	15-32	16
#16	1.19					0-15	13
#30	.595	13-22	21	8-13	12		
#100	.149	3-8	3				
#200	.074	1-4	3	3-5	3	0-3	2

Coarse and fine washed, crushed aggregates, were blended with sand to produce the above FIRL specifications using ASTM method designation C-136 for sieve analysis. ASTM procedures C-127 and C-128 were used to measure the bulk specific gravities of the aggregates which were necessary for determining the % air voids of the prepared samples. By definition , coarse aggregate is retained on a #8 sieve whereas fine aggregate goes thru it.

b. Marshall Values

The Marshall method provided the basis for determining the optimum asphalt content to produce a surface course with suitable strength for use on a roadway designed for medium traffic. This calls for a 50 blow compaction to each side of a prepared sample in a compaction mold 4" in diameter and 2-1/2" in length. We used a temperature of 325°F to mix our aggregates with the 85/100 penetration grade asphalt. A minimum mix stability value desired for such a roadway is 500 lbs, which was greatly exceeded in all mixes. Three samples of each aggregate gradation were prepared at three different asphalt contents for tests of stability, flow, permeability and percent voids. The stability and flow values as shown by data of Table 6 were obtained after the samples had been measured for permeability. The Marshall method requires that samples be immersed in a water bath held to 140°F± 1.8°F for 30 to 40 minutes before the stability and flow tests. We used an Instron test machine to compression-load the specimen at a constant rate of 2 inches per minute deformation to the point of failure. The total number of pounds required to produce failure at 140°F is recorded as its Marshall stability value. The deformation recorded for the specimen at its maximum strength is expressed in units of 1/100 inch as its flow e.g. if the specimen deformed 0.10 inch the flow value is 10. A flow value of from 8 to 18 is desired for medium traffic pavements and was satisfied by all specimens.

c. Permeability

The coefficient of permeability values (K) shown in Table 6 were obtained after 24 hours of aging at room temperature. As stated previously the samples were not extracted from the molds during this time since the bond between the specimen and the mold wall provided a seal to prevent side leakage errors for the permeability measurements. The molds were an integral part of the permeability apparatus. The constant head water bath was used to supply water flow through the specimen after it was evacuated with an aspirator for approximately 15 minutes. The hydraulic gradient across the specimen was measured with manometers placed directly above and below the specimen. Test runs were conducted at heads increasing by 1/32 in. for the California gradation, 1/6 in. for the British gradation and 1/4 in. for the Asphalt Institute gradation. These different head increments were required for each of the three gradations in order to establish the region of laminar flow where the velocity of water through the specimen is directly proportional to the hydraulic gradient across the specimen. This requirement must be maintained for Darcy's Law to be used in the computation of the coefficient of permeability. Departures from the linear relation (turbulent flow) became apparent at a greater than one inch head for the Asphalt Institute gradation and varied from 1/16 in. to 1/2 in. for both the British and California gradations. The laminar flow region was difficult to determine for the California and British gradations due to the fast rates through such open structures which accounts for the wide range of K values obtained for these specimens. Figure 5 is a view of water passing through a California specimen. It is easily seen from this Figure that high permeability values were obtained with this mix.

The data in Table 6 correlated extremely well for specific gravity and percent air voids. The permeability values, however, when compared to percent air voids do not in most cases correlate. It is felt that the turbulent region of flow through such open structures can not be eliminated from interfering with measurements of K values, and hence

Table 6

HOT MIX DESIGN DATA

Sample	% Asphalt	Gradation	SpG	Stability (lb.)	Flow (1/100")	% Air Voids	K(ft./day)	Seepage $\frac{d}{t}$ $\frac{in}{hr.}$
A-1	4.0	Asph. Inst.	2,183	1900	9	9.2	28	
A-2	4.0	Asph. Inst.	2,246	1900	9	6.6	15	
A-3	4.0	Asph. Inst.	2,195	1740	10	8.7	27	
			2,208	1846	9	8.2	23	1.15
Avg								
A-4	5.0	Asph. Inst.	2,264	1900	11	5.9	1.1	
A-5	5.0	Asph. Inst.	2,240	2050	11	6.9	2.2	
A-6	5.0	Asph. Inst.	2,237	1820	11	7.1	4.2	
			2,247	1923	11	6.6	2.5	.125
Avg								
B-1	4.0	British	2,185	1375	10	12.9	105	
B-2	4.0	British	2,142	1160	10	14.6	264	
B-3	4.0	British	2,228	1665	11	11.2	575	
			2,185	1400	10	12.9	315	15.8
Avg								
B-4	4.5	British	2,166	1520	13	13.0	528	
B-5	4.5	British	2,186	1675	13	13.2	779	
B-6	4.5	British	2,156	1380	14	13.4	228	
			2,169	1525	13	12.9	512	25.6
Avg								
B-7	5.0	British	2,227	1845	15	9.8	70	
B-8	5.0	British	2,338	2240	12	5.3	68	
B-9	5.0	British	2,219	1810	13	10.1	88	
			2,261	1965	13	8.4	75	3.75
Avg								
C-1	4.0	Calif.	2,018	1362	9	15.6	562	
C-2	4.0	Calif.	2,012	1264	9	15.8	352	
C-3	4.0	Calif.	2,021	1537	10	15.5	546	
			2,017	1388	9	15.6	487	24.4
Avg								
C-4	4.5	Calif.	1,956	1237	10	17.6	618	
C-5	4.5	Calif.	2,062	1596	10	13.2	1115	
C-6	4.5	Calif.	1,950	1097	10	17.8	1954	
			1,989	1310	10	16.2	1229	61.4
Avg								
C-7	5.0	Calif.	1,932	-	-	18.1	1531	
C-8	5.0	Calif.	1,999	1199	9	15.2	885	
C-9	5.0	Calif.	1,995	1079	12	15.4	1314	
			1,975	1139	10	16.2	1243	62.1
Avg								
C-10	5.5	Calif.	1,947	1350	10	16.9	3375	
C-11	5.5	Calif.	1,960	1200	9	16.3	3636	
C-12	5.5	Calif.	2,010	1500	8	14.2	3571	
			1,972	1373	9	15.8	3527	176

The asphalt (85/100 penetration grade) contents are based on percent by weight of total mix.

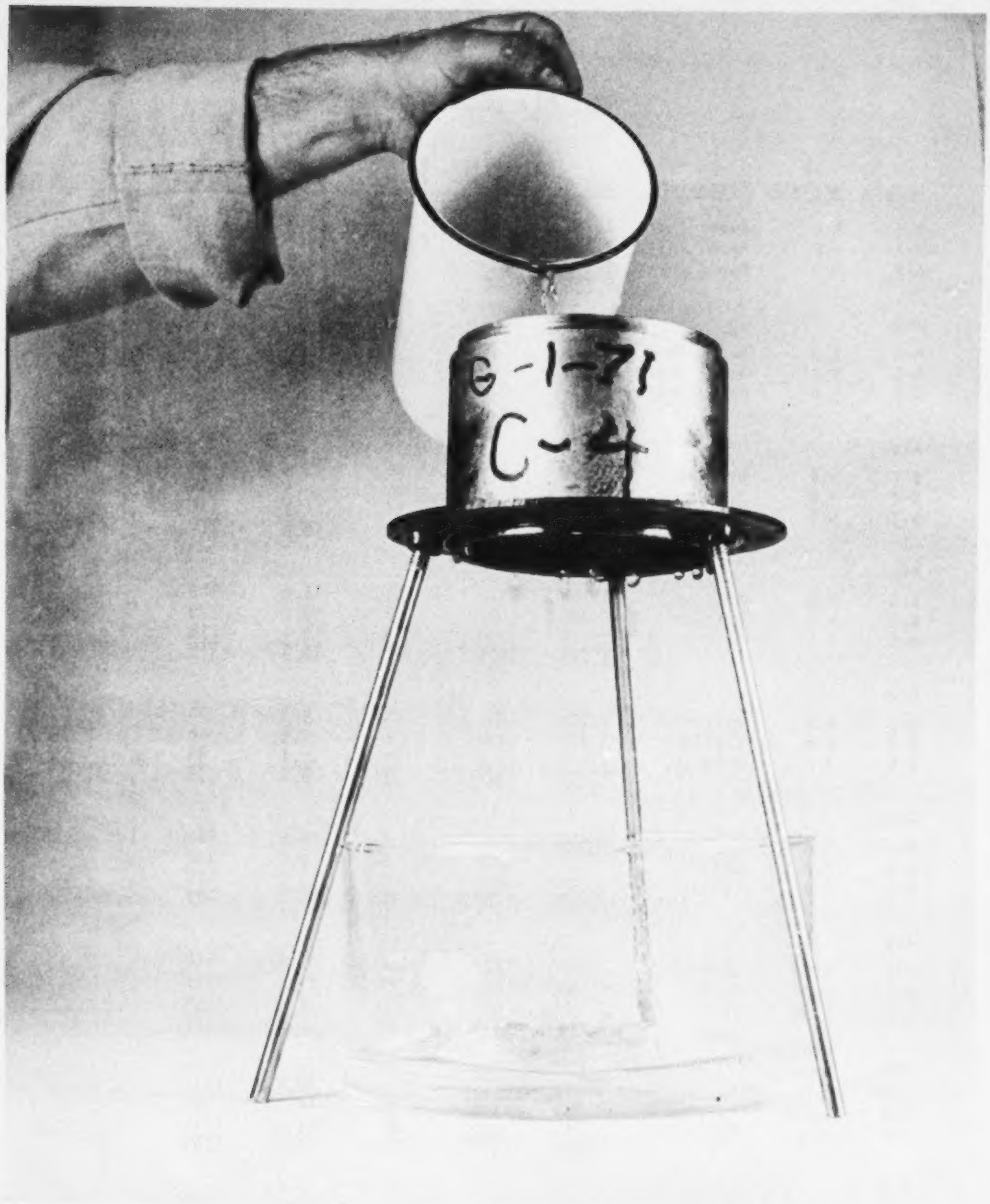


Figure 5. Water Passing Through a 4.5% Asphalt Content California Specification Sample

accounts for the discrepency. The values obtained, however, for permeability are felt to be the most reliable indication of the porosity of each specimen. The asphalt Institute mixes and the 5% asphalt content British mix are not adequate for handling heavy rainfalls. This is shown by their very low seepage rates. All other mixes are more than adequate to handle excessively large rainfalls i.e. greater than 15 in./hr of rainfall.

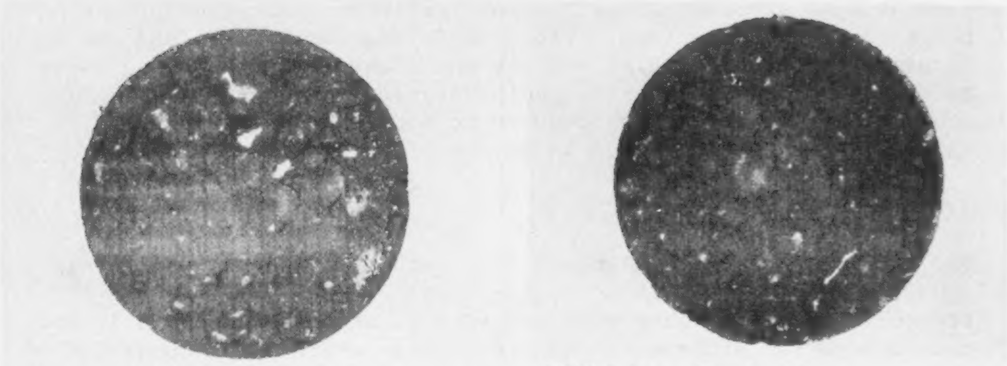
d. Freeze-Thaw

Two samples each of the Asphalt Institute, British and California gradation specifications at 4.5% asphalt content were used for freeze-thaw tests. They were prepared as discussed previously and put through the aforementioned freeze-thaw cycle. The condition of these specimens before and after 265 cycle is shown in Figure 6 and 7. Samples numbered one of each set were used as controls i.e. put through the cooling cycle, but not water soaked. Samples numbered two of each set were put through the regular freeze-thaw cycle. Two samples of each of a 5.5% Asphalt content (California mix) and a 4.5% asphalt content (California mix) containing 2% latex by weight of asphalt were also tested. Figure 8 shows the condition of these specimens after 233 cycles.

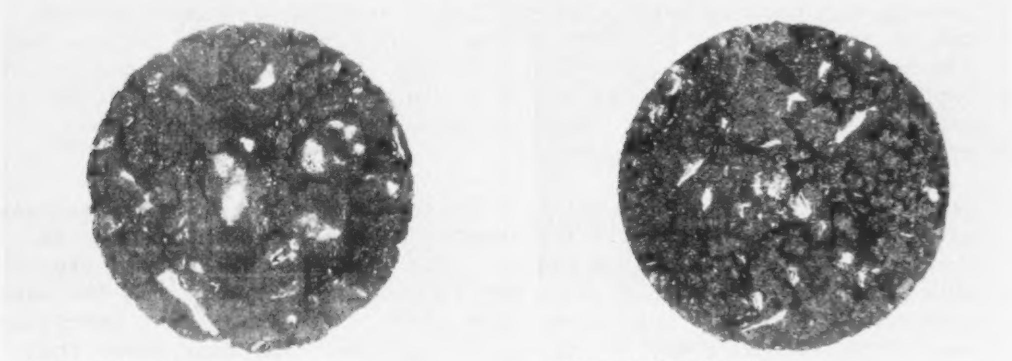
There was no physical dimensional change noted for any of the samples after the test cycles. All the samples were tested for changes in Marshall Stability and flow values. The results of this test are shown in Table 7, together with the range of values obtained for samples not put through the freeze thaw cycle. Values had not previously been obtained, however, for the latex samples. The data shows that both the stability and flow values for the cycled samples were not affected, and hence heaving problems would not occur for a drained porous pavement surface course.

e. Durability

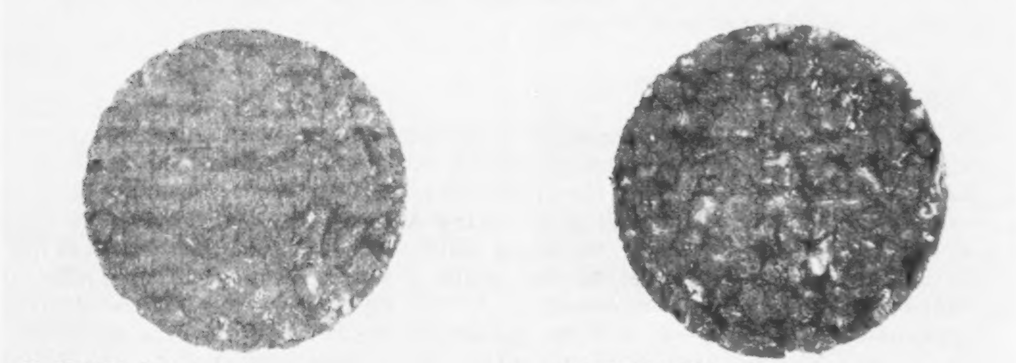
Two samples each of the Asphalt Institute and British gradations with 4.5% asphalt content were tested for asphalt penetration values after two weeks in the durability apparatus. The asphalt was extracted from the aggregate using ASTM specification D-1856 and measured for penetration using ASTM method D-5. The penetration values obtained are based on the depth a standard needle can penetrate into a sample maintained at 77°F. Conditions in the durability apparatus were 140°F at a 5 in. pressure head. The results as shown in Table 6 showed little if any difference when compared to the blank value obtained. The conditions then were changed to 150°F ± 5°F at 3 in. pressure head and an eight week continuous duration. The apparatus was operated at a 3 in. pressure head since 10 samples were being run continuously and all were readily porous which prevented obtaining the previous 5 in value. Two samples each of 4.5% asphalt content California, British and Asphalt Institute gradations were run as were



ASPHALT INST. (Sample #1) ASPHALT INST. (Sample #2)



BRITISH (Sample #1) BRITISH (Sample #2)



CALIFORNIA (Sample #1) CALIFORNIA (Sample #2)

Figure 6. Porous Asphalt Concrete Samples Prior to Freeze-Thaw Tests

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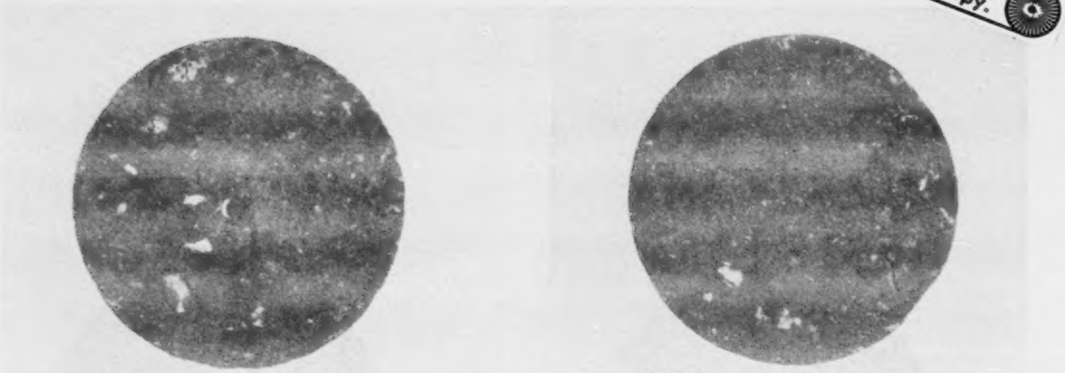
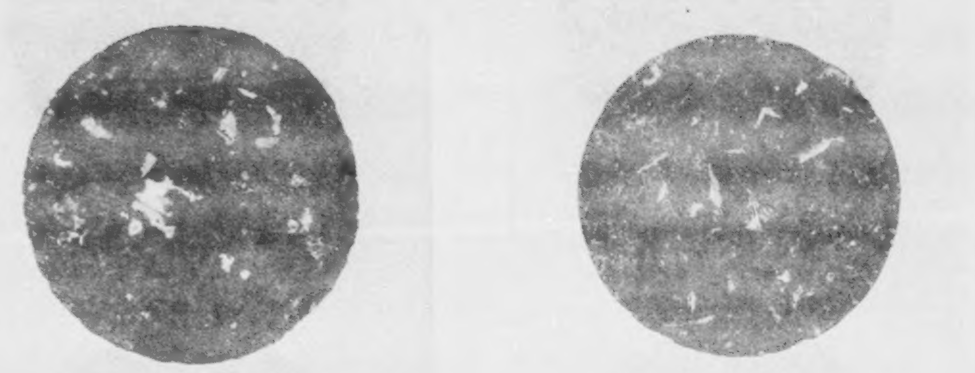


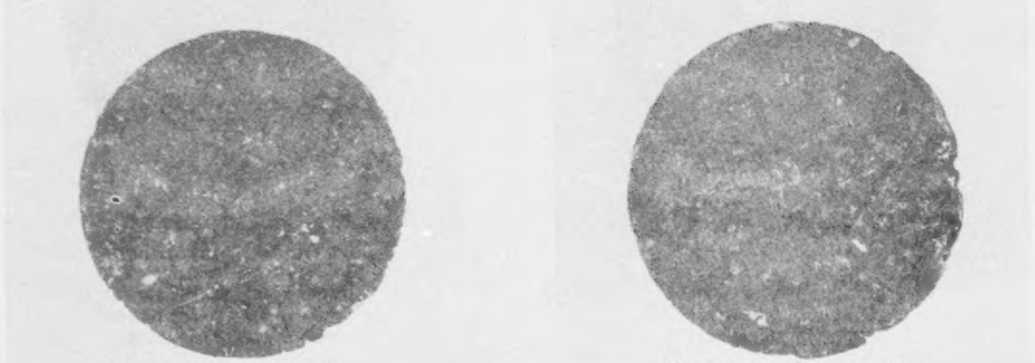
ASPHALT INST. (sample #1)

ASPHALT INST. (sample #2)



BRITISH (sample #1)

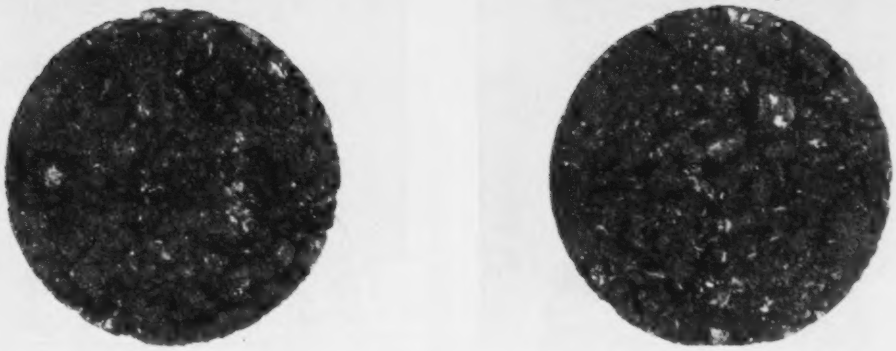
BRITISH (sample #2)



CALIFORNIA (sample #1)

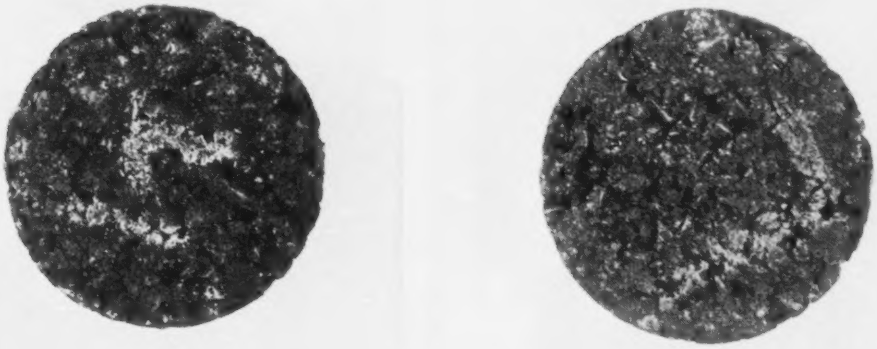
CALIFORNIA (sample #2)

Figure 7. Porous Asphalt Concrete Samples
After 265 Cycles Freeze-Thaw Tests



CALIFORNIA (Sample #1)
5.5% Asphalt Content
based on total weight

CALIFORNIA (Sample #2)
5.5% Asphalt Content
based on total weight



CALIFORNIA (Sample #1)
4.5% Asphalt Content
based on total weight
(2% latex content based
on weight of Asphalt

CALIFORNIA (Sample #2)
4.5% Asphalt Content
based on total weight
(2% latex content based
on weight of Asphalt

Figure 8. Porous Asphalt Concrete Samples After 233 Cycles Freeze-Thaw Tests

Table 7

FREEZE-THAW MARSHALL STABILITY VALUES

						Average Values Of Uncycled Samples (See Table 1)	
Sample	% Asphalt	Gradation	No. Of Freeze-Thaw Cycles	Stability (lbs.)	Flow (1/100")	Stability (lbs.)	Flow (1/100")
A_1 (Control)	4.5	Asph. Inst.	265	2200	12	1884	10
A_2	4.5	Asph. Inst.	265	2020	13	±150	±1
B_1 (Control)	4.5	British	265	2100	11	1525	13
B_2	4.5	British	265	1620	13	±150	±1
C_1 (Control)	4.5	California	265	1490	8	1310	10
C_2	4.5	California	265	1300	11	±250	±0
D_1 (Control)	5.5	California	233	1200	9	1373	9
D_2	5.5	California	233	1280	12	±180	±1
L_1**(Control)	4.5	California	233	1500	10		
L_1**	4.5	California	233	1470	11		

* % Asphalt based on total weight

** Contained 2% latex based on weight of Asphalt two containing 5.5% asphalt content California gradation and two with 4.5% asphalt California containing 2% latex by weight of asphalt. The asphalt penetration values for these samples are also shown in Table 8 along with the asphalt penetration value obtained for a 4.5% asphalt content California gradation which was aged for 8 weeks at room temperature.

Clark (see ref. 4) determined that one week of weathering of a mix in an oven at 150°F was equivalent to one year of natural weathering. This was based on service tests over a four year period. Using this criterion the results in Table 8 show the hardening process of the asphalt which may be expected after an eight year period in the field. The California (most porous) at 5.5% asphalt content is equivalent to the less porous Asphalt Institute and British mixes at the 4.5% asphalt contents. The 4.5% California mix shows the most hardening effect for the asphalt, which of course is due to its highly open structure. The addition of latex to this mix apparently had no effect. The 4.5% asphalt content California mix at room temperature also shows increased hardening. Since this was aged without heating or air flow through it, its hardening is attributed to the sorption of its light oils into the aggregate. This process is speeded by raising the temperature, and is believed to account for most of the hardening shown in Table 8. Apparently the 5.5% asphalt content would have to be the minimum amount for use with the California gradation. This information has been borne out by tests being conducted by the California highway transportation agency.

f. Traffic Hazard Considerations

Considered here are pavement improvements over and above the desirability of water infiltration into the soil.

Skid Resistance And Visibility

Research on factors improving the friction characteristics of pavements have shown that braking forces on wet pavements are more dependent on the surface characteristics of pavements than on the tire or tread (See Ref. 5). Additionally, this study found that aircraft tire wear was not excessive on open graded mixes and that braking forces were not directional as they are with grooved pavements. The basic finding was that drainage under the footprint was sufficient to prevent aqua-planning and would not necessitate the use of a grooved tread, with the attendant disadvantage of inadequate drainage when the tire ribs are worn away.

A similar finding has been reported from California with open-graded mixes permitting lateral drainage of rainfall to the edge of pavements (See Ref. 6).

A secondary, but nevertheless important feature in accident prevention is the better visibility of pavement markings expected during

Table 8

ASPHALT PENETRATION VALUES AFTER AGING IN THE DURABILITY APPARATUS

(Asphalt penetration blank = 94)

Sample	% Asphalt	Gradation	Asphalt Penetration Value, dmm. 2 weeks @ 140°F, 5" head	Asphalt Penetration Value, dmm. 8 weeks @ 150°F, 3" head
A_1	4.5	Asphalt Institute	92	28
A_2	4.5	Asphalt Institute	92	30
B_1	4.5	British	92	33
B_2	4.5	British	92	26
C_1	4.5	California		17
C_2	4.5	California		18
D_1	5.5	California		30
D_2	5.5	California		29
L_1*	4.5	California		16
L_2**	4.5	California		43 (room temp.)

* % Asphalt based on total weight.

** Contained 2% latex based on weight of asphalt.

periods of heavy rainfall with porous pavements. Water cannot build above the surface to change the reflective appearance.

These two features, improved skid resistance and visibility, are considered very important plus factors in pavement design, especially since these properties can be obtained at little or no additional pavement surface cost.

SECTION IX

HYDROLOGICAL CONSIDERATIONS

Hydrological considerations are important to the concept of porous pavement in two respects: first, the expected maximum precipitation will affect the required sub-pavement reservoir capacity as well as in some instances, the viability of porous pavement itself and second, the extent of the frost-period will dictate variations in the thickness of conventional pavement, thereby influencing the relative economics of conventional versus porous design. These two areas are discussed separately below.

1. Maximum Expected Precipitation

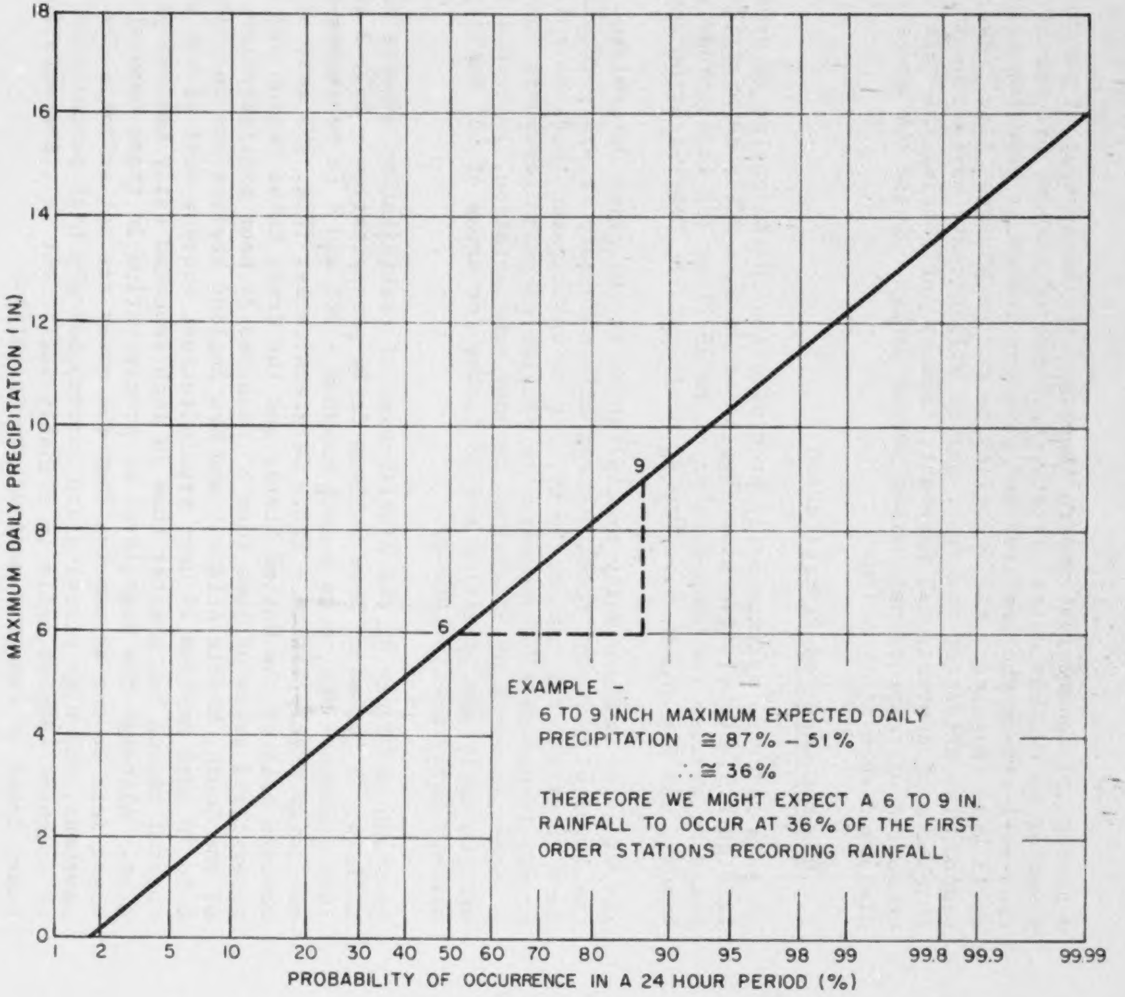
Data on recorded maximum daily precipitation in the nation is presented in Figure 9, "Cumulative Distribution of Maximum Daily Rainfall," (data based on maximum recorded U.S. point rainfall at 288 first order stations), and Figure 10, U.S. Map of Maximum Daily Precipitation Zones.

The expected maximum daily precipitation is the prime determinant of the level of pavement reservoir capacity necessary to store runoff before it percolates into the soil. It is anticipated that the following gravel layers will be necessary to provide adequate reservoir capacities: 7 inches in areas of 3" maximum 24 hour precipitation, 14 inches for 6" maximum daily precipitation and 28 inches for areas of 12" anticipated maximum daily precipitation.

As shown in Figure 9, the distribution of precipitation amounts is as follows: 3 inches or less maximum daily precipitation - 15%, 3 to 6 inch maximum - 36%, 6 to 9 inch maximum - 36% and 9 to 12 inches maximum daily precipitation - 12%. Geographically, (Fig. 10) most of the western half of the United States and the Great Lakes region are in generalized areas of less than 6" recorded 24 hour precipitation. Most of the South, Middle Atlantic and New England regions are in areas of 6 to 10 inch maximum 24 hour precipitation, whereas most of the southern coastal region has greater than 10 inch expected daily maximum precipitation. Although the high level of precipitation in these coastal areas might lead to the assumption that the areas are not suitable for porous pavement, the high porosity and correspondingly high percolation rate of southern coastal soils is probably sufficient to compensate for the heavy level of expected maximum precipitation.

2. Freeze/Thaw Susceptibility

The length of the frost period is a major determinant of pavement susceptibility to freeze-thaw damage. In areas of extensive frost, ice forms in frost-susceptible soils causing a raising of



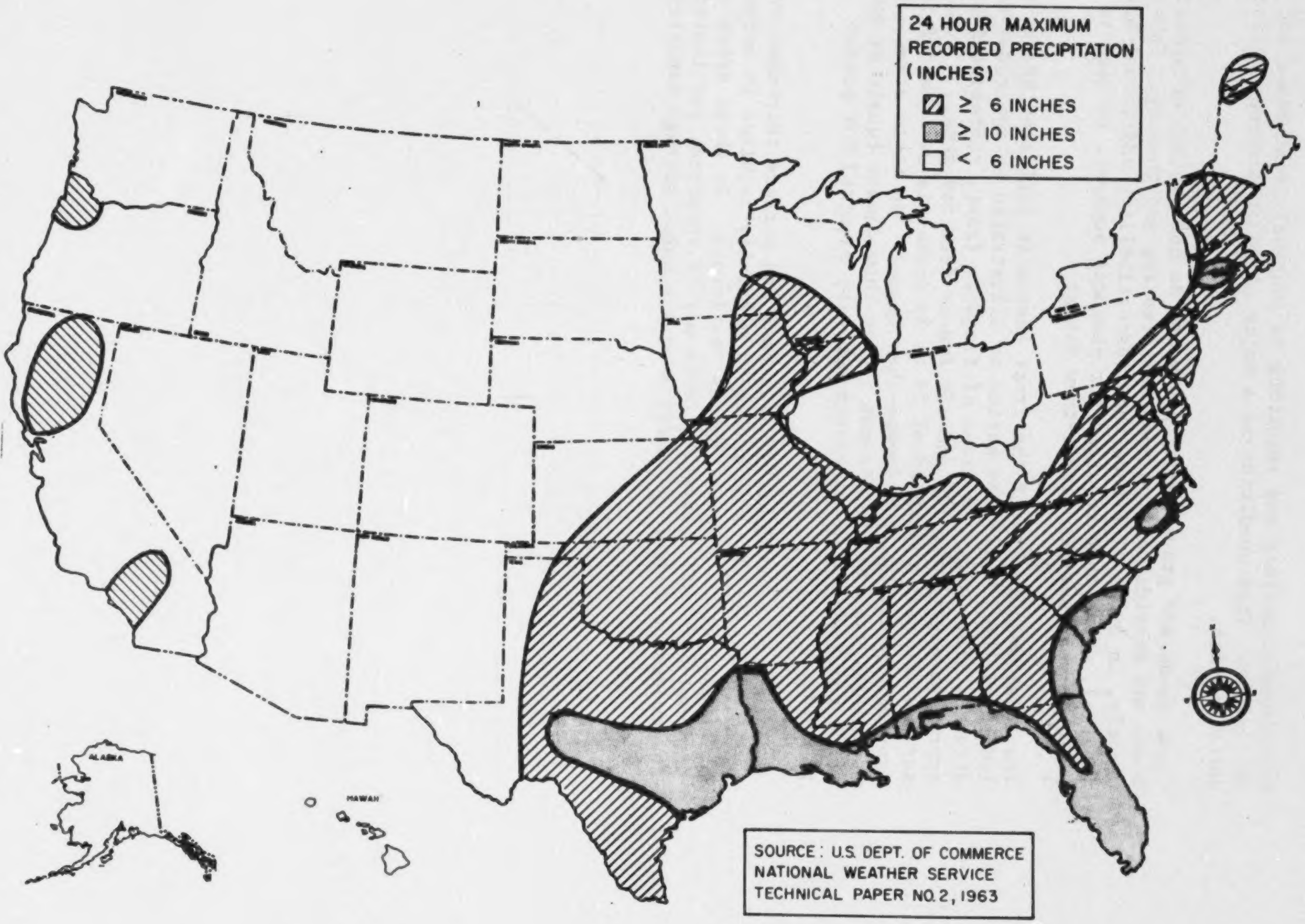
EXAMPLE –

6 TO 9 INCH MAXIMUM EXPECTED DAILY PRECIPITATION ≅ 87% – 51%

∴ ≅ 36%

THEREFORE WE MIGHT EXPECT A 6 TO 9 IN. RAINFALL TO OCCUR AT 36% OF THE FIRST ORDER STATIONS RECORDING RAINFALL.

Figure 9. Cumulative Distribution of Maximum Daily Rainfall


24 HOUR MAXIMUM RECORDED PRECIPITATION (INCHES)
▨ ≥ 6 INCHES
▩ ≥ 10 INCHES
☐ < 6 INCHES
ALASKA
HAWAII

SOURCE: U.S. DEPT. OF COMMERCE
NATIONAL WEATHER SERVICE
TECHNICAL PAPER NO.2, 1963

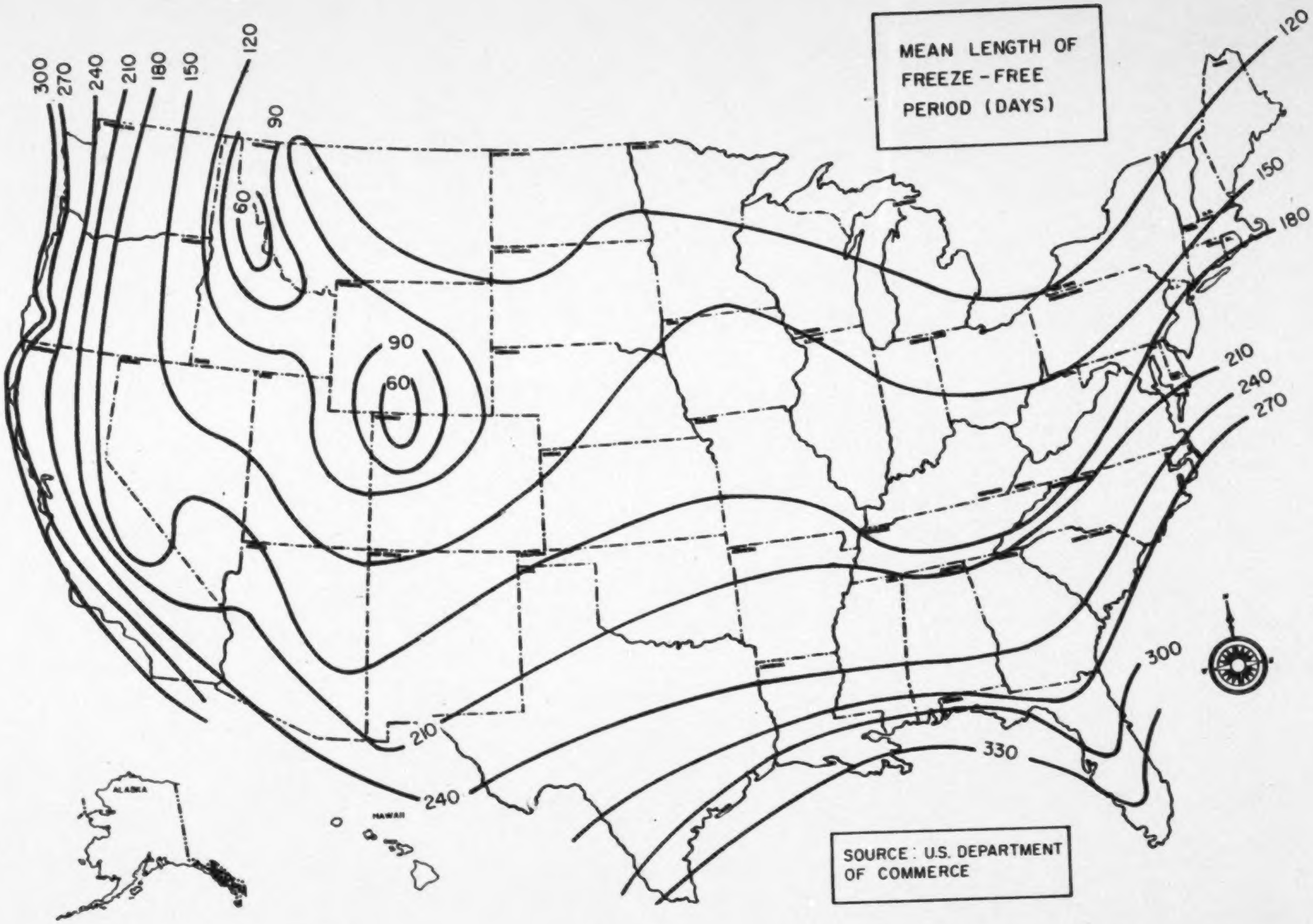
Figure 10. U.S. Map - Maximum Daily Precipitation Zones

the pavement surface and resulting in seasonal frost-heave and settlement. This condition is a major cause of pavement surface deterioration.

Clean sands and gravel under pavements do not exhibit detrimental heave and subsidence from seasonal freezing and thawing. Consequently, in areas of freeze-thaw susceptibility, additional base material, above that required for pavement support, is used to overcome road surface freeze-thaw damage.

The relative duration of the frost season is indicated by the mean length of the freeze-free period as illustrated in the zonal map attached (Fig. 11). In areas of frequent frost, corresponding approximately to the 120 and 150 freeze-free day zones, a total surface and base thickness of 28 to 36 inches is recommended to provide protection from freeze-thaw damage. In these areas, the base layer required to prevent freeze thaw damage equals or exceeds the gravel base reservoir capacity required for porous pavement.

In contrast, a total high design base and surface thickness over normal soils of 16 to 18 inches is generally required in areas of limited frost period, such as California. In these areas additional base and excavation costs may be incurred, particularly in low-design roads, to create adequate water storage capacity.


MEAN LENGTH OF FREEZE-FREE PERIOD (DAYS)
300
270
240
210
180
150
120
90
60
90
60
120
150
180
210
240
270
210
240
300
330
ALASKA
HAWAII

SOURCE: U.S. DEPARTMENT OF COMMERCE

Figure 11. Mean Length of Freeze-Free Period

SECTION X

DRAINAGE OF POROUS ASPHALT CONCRETE PAVEMENT STRUCTURES

If tests indicate that the subgrade is too impermeable to drain the base course reservoir within a reasonable amount of time, it will be advisable to provide a supplementary drainage system. There are a number of popular drainage designs capable of adequately removing the water remaining in the base course. Several of these are:

1. French Drain

This system utilizes coarse open-graded rock in relatively deep pits or trenches. This type of drain can be expanded out at the lateral edges of a roadway to provide a deeper system with more water holding capacity, so that the water has more time to percolate through a less permeable subgrade. Such as system is shown in Figure 12a.

2. Sand Drain

This system is similar to the French Drain but the coarse open-graded rock also contains enough fines to prevent intrusion of adjacent soil which may tend to clog the drain. This clogging is dependent upon the nature of the subgrade soil. Again this system could be expanded to provide more water holding capacity (see Fig. 12b).

3. Two-Layers Systems

With this type system a subbase is provided as a filter medium. The coarse open rock drain layer (base) is protected by a suitable filter layer (subbase) such as clean concrete sand. This system generally provides excellent resistance to clogging and provides excellent drainage capacity after numerous years of service. This system is shown in Figure 12c.

4. V-Trench Water Removal to Pond

A positive method of removal of water contained in a French Drain type system is to use the base material as a drain for transport to a relatively shallow V-trench at a low point in the cross section of the roadway. If a heavy volume of water is expected, it may be advisable to obtain greater drain capacity by the construction of a two-layer system. If an appreciable gradient is involved, a cross-drain should be placed at the downhill end of the cut. This will intercept any water flowing longitudinally which if not drained could saturate the fills and cause slumping of the fill slopes. The V-trench shown in Figure 12d could be emptied into a

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storage pond or other suitable drainage system. The profile of a road showing cross drains which empty into the V-trench is shown in Figure 12e.

5. Pipe Drains

Subgrade soils which are for all practical purposes impervious to water would necessitate the use of pipe drains. The pipe is generally perforated with 1/4 to 3/8 inch diameter holes, placed in two or more double rows 90° to 120° apart running lengthwise of the pipe. Materials of construction include aluminum alloys, asbestos cement, bituminize fiber, cast iron, clay, concrete, and plastic. They are available in sizes ranging from 4 inches to 120 inches and larger in diameter. The sizes and type pipe to be used would be determined by the conditions set for drainage. Such a system is shown in Figure 12f.

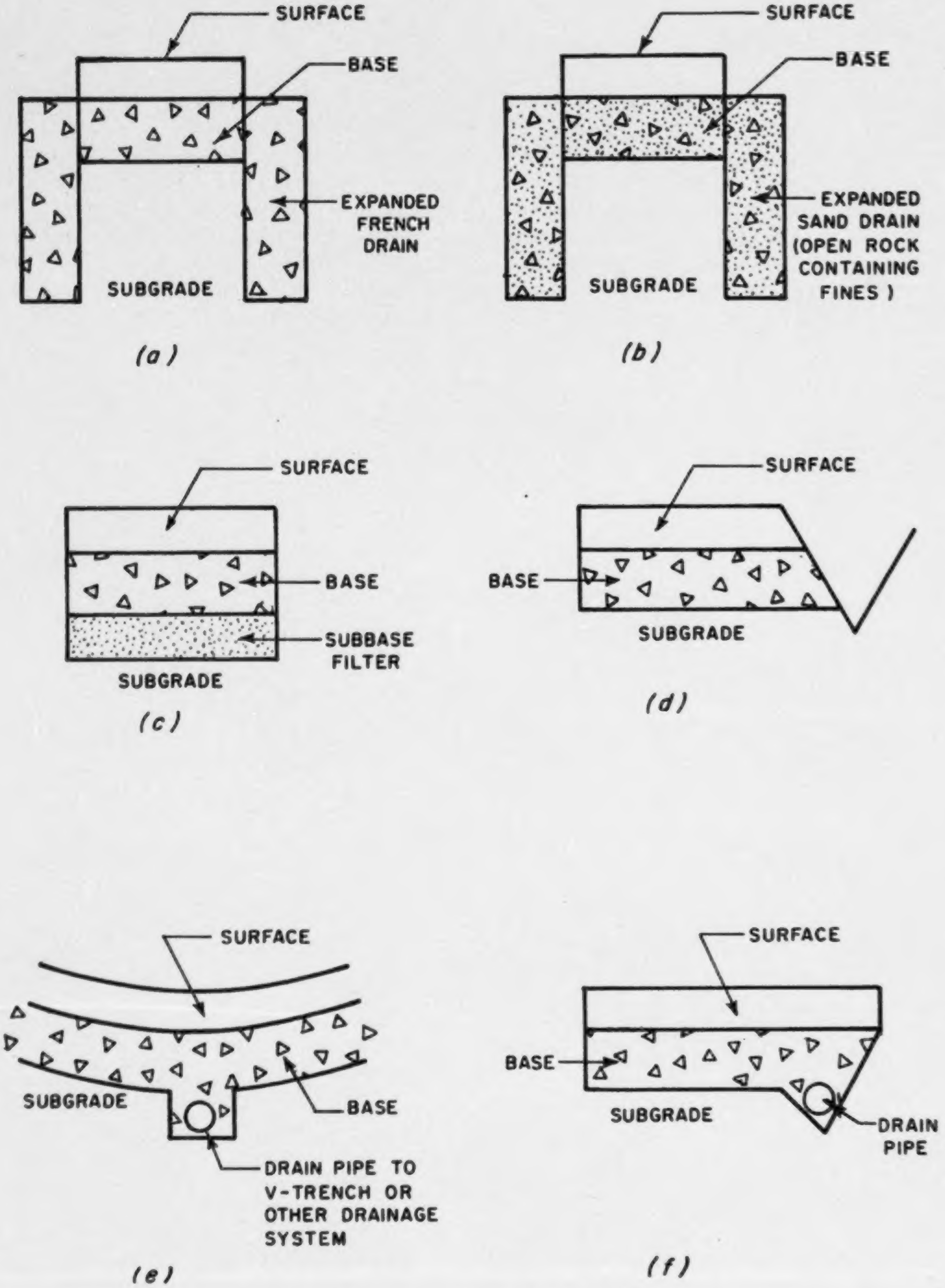
SURFACE
BASE
EXPANDED FRENCH DRAIN
SUBGRADE
(a)
SURFACE
BASE
EXPANDED SAND DRAIN (OPEN ROCK CONTAINING FINES)
SUBGRADE
(b)
SURFACE
BASE
SUBBASE FILTER
SUBGRADE
(c)
SURFACE
BASE
SUBGRADE
(d)
SURFACE
SUBGRADE
BASE
DRAIN PIPE TO V-TRENCH OR OTHER DRAINAGE SYSTEM
(e)
SURFACE
BASE
SUBGRADE
DRAIN PIPE
(f)

Figure 12. Supplementary Drains

SECTION XI

THE POLLUTION EFFECT OF URBAN RUNOFF

A literature investigation was carried out primarily to determine the water pollution hazard from urban runoff. What actually is present in urban runoff that would constitute a potential pollution hazard? Where does it come from? How and why does it reach the receiving stream? What can be done to prevent it? And how would a porous pavement system alleviate the above problem?

In 1969 The American Public Works Association under contract to The Federal Water Pollution Control Administration (Contract No. Wa 66-23) made a study on the causes and remedies of water pollution from surface drainage in metropolitan Chicago, Ill.(7) The study points out that street refuse transported by runoff is a significant source of pollution in the receiving stream.

Here street refuse is defined as the accumulation of materials on the street, sidewalk, or along the curb and gutter which can be removed by sweeping. Components or particles larger than 1/8" diameter are called litter; those smaller than 1/8" diameter are classed as dust or dirt.

In May 1967 a survey was made of 500 cities of various sizes and locations in the nation. The purpose of the survey was to identify the major refuse producing sources in the various communities. One hundred forty-nine cities replied. The survey disclosed six major sources of street litter:

(1) spillage from overloaded trucks, (2) yard refuse (leaves and lawn clippings), (3) improperly used trash receptacles, (4) debris from construction and demolition, (5) roadside dumping, (6) poor public cooperation.

The amount of refuse deposited from various sources was determined by a study(7) of 18 representative areas in Chicago to be from 0.5 to 8 pounds/100 ft. of curb/day. The average varied from 4.7 for commercial areas to 2.4 for single family residential areas. A total yearly summary of estimated street litter and dust from a 10 acre residential area in Chicago showed the following components: rags, .018 tons; paper, .432 tons; dust and dirt, 6.6 tons; vegetation 2.22 tons; inorganics, 1.08 tons. The most significant component in terms of potential pollution hazard is the dust and dirt fraction which varied from 0.4 to 5.2 lbs./100 ft. of curb/day. Of this material approximately 3% was soluble and readily transportable. The soluble material contained appreciable amount of contaminants measured as: BOD (5mg/g), COD (40mg/g), nitrogen forms (0.48 mg/g), phosphates (>0.05 mg/g), total bacterial count ($>10^7$/g), coliforms ($>10^6$/g), and fecal enterococci (5400/g).

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It is seen that dust and dirt are the predominant pollutants. The coarse or crude litter aside from representing an esthetic pollutional hazard, can be washed into street inlets and catch basins where they decompose and create an additional oxygen demand on the receiving waters.

The study disclosed that the liquid remaining in catch basins between precipitations tends to become septic and the solids trapped in the basin take on the characteristics of anerobic sludge. During even minor rainfall the displacement can release a major amount of this septic material into the sewer system.

On the basis that contact between street litter and precipitation runoff water could occur with a 14 day accumulation of material and that all of the soluble and transportable BOD would be discharged into the street inlets during a two hour storm, the peak flush effect on receiving waters per mile of street could be 160% of the raw sewage BOD and 800% of the secondary treatment effluent during the two hour runoff period.

Thus one can see that "clean" storm waters are polluted. Rain scavenges air pollutants out of the atmosphere, flows across roofs across grass sprayed with insecticides and herbicides and fertilized with inorganic nitrogen and phosphorous, across pet and bird droppings along street gutters and finally through catch basins where the flow may displace perhaps 2 cubic yards of stagnant water and carry with it some of the digested solids from the bottom of the catch basin. By the time the storm water reaches the interceptor, it may exceed the polluting strength of sanitary sewage. When salts from snow and ice control, lead and other contaminants from automobile exhausts are added, the storm water may have a wide range of undesirable characteristics.

Overflows from combined sewers are identified as sources of pollution.

In dry weather the small volumes of domestic sewage in large combined sewers results in low velocities. Solids therefore settle out along the sewer line. Storm flows tend to scour this material out and carry it to the overflow. It has been estimated that from 3 to 5% of the total organic load reaching the sewer leaves by overflow.

The American Public Works Association was asked to estimate the cost of separating combined sewers nationwide. They estimated a cost of $48 billion dollars (1967). They also estimated a cost of $15 billion for alternate methods of treatment and control.

Anoth. finding of the survey indicated that less than 20% of the combined sewer overflow regulators could be adjusted to meet various flow criteria. Of the 10,025 regulators found in the jourisdictions interviewed, 40% were nothing more than simple wires, many with design features which are not responsive to overflow regulation.

One question remains to be answered. How would a porous pavement system alleviate or at least reduce the above problem?

Depending on the pore size of the system in question, much of the dust and dirt fraction would be washed through to the underlying soil. The soluble portion of the dust and dirt fraction along with any other biodegradable wastes would be washed through to nature's own waste treatment plant, the soil.

Pesticides, herbicides, air pollutants, nitrate and phosphate fertilizers would also be washed through where they would probably be metabolized by soil bacteria.

Catch basins would not be needed with a porous pavement system, thereby eliminating the septic sludge which builds up in them and saving the cost of having them cleaned periodically.

The only problem remaining is that of the debris which is too coarse to be washed through the pavement system. This problem can only be solved by better "housekeeping" practices on the part of the area residents and more efficient street cleaning procedures in our municipalities.

SECTION XII

BACTERIOLOGICAL EFFECTS OF POROUS PAVEMENTS

The activity of soil bacteria serves to decrease the quantity of organic pollutants carried into the soil by surface waters. Under normal conditions in the top layers of soil, the bacterial processes by which the pollutants are oxidized draw on oxygen dissolved in the surface water or soil moisture. If air is excluded from the process, the dissolved oxygen is rapidly depleted and other sources of oxygen are used. The first alternate source is the oxygen in nitrates and nitrites contained in the soil, and the results of the reduction of these materials is the appearance of ammonia nitrogen in the percolating waters. The second source of oxygen is from the reduction of sulfates, with sulfides, usually as iron sulfide accompanied by hydrogen sulfide, as an end product.

While the degree to which pollutants are oxidized before reaching the water table is dependent on the time the pollutant takes to traverse the area of bacterial action, reducing the air supply to this area would lead to reduction of the alternate sources of oxygen and generate objectionable odors and compounds. Over a longer period the alternate sources of oxygen could be exhausted and little change would occur in the dissolved pollutants.

Experimental

In determining the effect of porous pavement on the activity of soil bacteria, two test tanks were used. One tank contained no pavement while the other contained a porous asphalt concrete pavement sealed to the tank walls. Water was allowed to percolate through the test tank at five day intervals and samples of the percolated water were drawn off.

The tests performed were:

1. BOD - Used to determine whether pollutants were percolating through the soil in the tank and to assess bacteriological activity. Unless pollutants are added to the tanks, a progressive lowering of the BOD should occur since the amount of soil, hence amount of pollutant, in the tank is finite. If BOD tests are carried out without seeding, and if the BOD disappears from the tank, it would indicate that bacterial food had been exhausted. Intentional addition of a bacterial food should reestablish bacterial activity and a BOD should be obtained without seeding the samples.

2. COD - Used as a check on BOD. COD should exceed the BOD and should normally decrease if BOD decreases.

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3. Ammonium Nitrogen - Used as first indication of the establishment of anaerobic process.

4. Sulfides - Used to indicate a well established anaerobic process.

Test Results

The test results are tabulated in Table 9. BOD results varied but were generally at a low value during the first three sampling intervals. In order to boost the BOD, the tanks were treated with Peptone Solution between the 3rd and 4th sampling periods. The tank without the test pavement immediately showed a BOD increase but the tank with the pavement showed a continued decreased BOD. The 5th period BOD samples showed an algal growth since the dilutions were inadvertently exposed to light. This would account for the lack of BOD since oxygen was being replenished by the Algae. The lag of BOD recovery in the tank containing the test pavement seems to indicate that the solution of organic "food" was not transmitted to the lower layers of the soil in the tanks as rapidly as in the tank with no pavement. This would be advantageous since the material would not penetrate to the water table as rapidly and bacterial processes would have longer to act on it.

The BOD results are supported by the COD results. The COD decreased by the 4th sampling period but did not increase thereafter as rapidly for the tank containing the pavement as for the tank containing no pavement.

In none of the samples was ammonium nitrogen increased above the background value, and sulfide was not detected. This would indicate that the bacterial processes in both tanks remained aerobic.

Table 9

BACTERIAL ACTIVITY DATA

Sample No.	1		2		3		4		5	
	With	Without	With	Without	With	Without	With	Without	With	Without
5 day BOD (ppm)	4.86	7.56	∿0	∿0	4.86	4.86	1.62	12.42	∿0	∿0
COD (ppm)	22.24	31.14	22.24	35.58	26.69	4.45	0	--	8.89	57.82
NH_4 Nitrogen	.4	.3	.2	.2	.3	.2	.2	.2	.2	.2
$S^=$ (ppm)	0	0	0	0	0	0	0	0	0	0
Fe (ppm)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

Soil and water samples from both tanks were cultured in nutrient agar after sampling period 5 and all showed profuse colony growth. Colonies were largely bacilli of at least two different types as shown by Gram stain.

Indications from these relatively sketchy experiments are that the use of the porous pavement does not have an apparent inhibitory effect on aerobic bacterial processes, and may in fact promote BOD reduction. More extensive testing, including studies of out-door demonstration pavements, are needed to remove all doubts on this point.

SECTION XIII

SPECIAL PAVEMENT TYPES

In order for a material to be considered a good candidate for surfacing recreational areas at least 4 criteria must be met. First, the material must be non-abrasive and resilient enough to cushion falls. Secondly, it must be tough enough to withstand foot traffic and vandals. Next it should be porous enough so that rainfall drains through rapidly. Finally, it should be long lived and economical.

Approaches tried by the City of Philadelphia include:

(a) Tanbark matting, which is loose and tends to spread away from the play area. It is also becoming expensive and difficult to obtain.

(b) Foam mats, such as Tartan and Safety-Turf polyurethane mats, which are laid over black-top. They are soft and resilient, hold rainwater like sponges, and are very slippery when wet. Cost \$25-30/yd^2.

(c) Monsanto's Astroturf over black-top like the foam mats, is resilient, water retentive, \$30/yd^2, safe when dry and slippery when wet. Franklin Field has an 18 inch crown, which still is not enough to drain the material properly. In the Veteran's Stadium, a vacuum cleaner is to be used to suck up water.

A Monsanto M-10 Astroturf was found to have an impervious closed cell foam backing. When many holes (1/8"dia., 1/4" apart) were drilled through this, the piece was amply permeable to bulk water, but would not drain dry.

In view of the shortcomings of these materials, we took another approach:

Resilient porous surfacings were made by chopping rubber tubing into pieces 1/2 to 5/8 inches long, coating them with an adhesive and pouring them at random into a mold. Mats 1" to 1-1/2" thick were thus prepared, as described in Table 2. Voids constituted 46 to 64% by volume of the mat, and the equivalent of one inch of rainfall drained through them in considerably less than 15 minutes.

The mats were all bonded and resilient, and were judged to possess good mechanical properties for a playground surface. If damaged by vandals they could be repaired by cementing more tube pieces into the breach.

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The samples would weigh 18 to 25 lbs./yd^2, and based on the costs for bulk rubbers probably would cost a minimum of about \$7.00/yd.^{2}, with \$10-12 more likely. Based on commercial extruded tubing costs, this mat product would cost at least twice these figures.

Adhesives used successfully were Armstrong D-200 cement for gum rubber, Goodrich A862B Cement for Neoprene, and tetrahydrofuran for polyurethane. Time did not permit a survey and evaluation of all the products being offered commercially for playgrounds. A study of these might disclose materials that could be modified to make them porous, while still preserving their necessary durability and resiliency.

Colored Pavements

The economic study (Sec. XVII of this report) indicates a broad demand for color-infused asphalt pavement, for which a premium of \$0.30 to 3.00 per square yard could be expected. The colors, preferably light earth tones, are desired to provide a more restful setting in residential areas, and to eliminate unpleasant heat absorption. Brighter colors could be used for color-coding of deceleration lanes and traffic routings.

Three design approaches to colored pavements were considered:

(a) Use a light colored binder in place of asphalt in asphalt concrete. Such binders were marketed a few years ago by Humble Oil and Refining Company, Neville Chemical Company, and Carlisle Chemical Company. Three difficulties were encountered:

1. Dirt adhered to the binders, obscuring their colors. Removal of the dirt was impractical.

2. As a properly-formulated asphalt concrete wears, aggregate surfaces are exposed and the binder is confined to the spaces between the rocks. Thus the dominant color becomes that of the aggregate itself.

3. Because the colored binders were relatively expensive, it was desired to use them in thin layers. Construction of these layers was difficult, and under continued traffic they tended to wear away, exposing the base pavement.

(b) Colored aggregate was used, with asphalt binders, in normal asphalt concrete formulations. This has been very satisfactory in localities where a suitable natural colored aggregate is available (Route 940 near the North East extension of the Pennsylvania Turnpike, for instance).

(c) Colored granules normally used in prepared roofing can be spread over a resin adhesive layer on the pavement. The resin can be applied as a hot-melt, cut back with solvent as a varnish, or emulsified with water. Two such coats provide excellent hiding of the base pavement.

The color of roofing granules resides in a ceramic layer on their surfaces. This may tend to chip off under continued heavy traffic, necessitating a re-application to restore the color.

We obtained a proprietary resin mixture cut back with heptane from Velsicol Chemical Company, and roofing granules from GAF Corporation, Hagerstown, Maryland. Two coats of varnish on which granules were spread, were applied to a sample porous pavement of the California design. They cut its porosity in two, but the resulting product remained sufficiently permeable for any intended installation in the U.S.

Installed cost is estimated to be 35 to 60 cents per square yard. Color coatings of various sorts sometimes are used on playgrounds and tennis courts; these generally are paint-like materials and may contain sand to enhance their friction characteristics. Before these should be used on porous pavements, it should be demonstrated that they will not cover over or block the pores.

SECTION XIV

CONVENTIONAL PAVEMENT COSTS

Porous pavement has been considered for use in constructing the following types of pavements: parking lots, residential and business streets, county roads and highways, playgrounds, sidewalks, public squares, and airport runways. Two design levels are considered for both residential and business streets; county roads and highways are divided into four classifications based on average traffic volume.

In this Section, standard pavement design, storm drainage provisions and the installed cost of pavement and storm sewers are discussed for each of the above conventional pavement categories. Summaries of the cost and design of these conventional pavements are given in Tables 10 through 12.

In Section XV, "Maintenance and Resurfacing Costs," the average annual cost of pavement and drainage maintenance and of pavement resurfacing is assessed to determine the relative maintenance cost range to which porous pavement must adhere in order to be competitive with conventional surfaces. In Section XVI, "Porous Pavement Benefits," the economic value of benefits to be derived from porous surfaces is evaluated. Benefits assessed include relief from combined-sewer overflow pollution, augmentation of local water supplies, relief from flash flooding and aesthetic enhancement. In Section XVII, "Market Demand for Porous Pavement," the gross annual demand for conventional surfaces is estimated, the cost of equivalent porous design is compared with the cost of conventional pavements, and the potential demand for porous pavement is established on the basis of the comparative cost and the benefits to be realized from porous pavement.

A. PARKING LOTS

Data on parking lots were obtained from a number of private builders and developers for a standard, large-scale parking lot of approximately 50,000 square yards.

Pavement Design

Because parking lot maintenance and resurfacing are generally the responsibility of the ultimate owner rather than the developer, parking lots are typically characterized by a very low level of pavement design. Standard parking lots are constructed with a 4 to 6-inch thick crushed-stone base and a 1-1/2 to 2-1/2-inch thick asphaltic surface. In urbanized areas — cities and Standard Metropolitan Statistical Areas — where specifications are stricter, a 6-inch base and a 2 to 2-1/2 inch surface are normal. In outlying areas where specifications are less stringent, 5-1/2 inches in total thickness is typical.

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Base costs have been estimated from primary and secondary sources at from $1.30 to $1.60 per square yard and surface costs at from $1.30 to $1.90 per square yard, yielding an average total pavement cost of $3.05 per square yard. Although smaller parking lots have the same basic design, the unit installed cost is inflated because of the small surface area. Costs such as excavation and grading have not been considered in this and subsequent analyses since they are invariant to the pavement type.

Storm Sewers

Discussions with developers have established that storm-sewer facilities are almost invariably required by local building codes for large-scale parking lots in both urban and outlying areas. In standard practice, one storm inlet is provided for every 2000 square yards of surface area. When unusual terrain and/or runoff prevails, more inlets may be required. The linear feet of storm drainpipe varies with the locale and depends on whether runoff is directed to an existing nearby trunk sewer system or outflowed directly to a receiving watercourse. Estimates obtained from the City of Philadelphia, the town of Columbia, Maryland, and several developers indicate that the cost of storm sewers ranges from $1.05 to $2.06 per square yard of surface area. The low figure is typical of an inner city parking lot where little piping is required to link storm inlets with an existing street sewer system; the high figure represents an outlying area where more extensive provisions are required. When a high water table or other local condition necessitates the removal of subsurface water from the paved area, underdrain pipes are sometimes installed at an extra cost of approximately 15¢ per square yard.

B. RESIDENTIAL STREETS

Since the basic construction of residential streets varies considerably, residential roads were classified by design level — low design and high design — and are discussed separately below.

Pavement Design

Low-design residential streets are typically located in suburban and outlying developments where county specifications are less stringent than those in cities. Typical construction consists of a 5 to 6-inch fo crushed stone with a 1-1/2 to 2-inch asphalt surface. The low end of this range — 6-1/2 inch total thickness — is generally observed in such outlying developments as Columbia, Maryland; the higher level of the design range — 8-inch total thickness — is typical of suburban counties within metropolitan areas. Total cost for these low-design residential streets ranges from $3.00 to $3.60 per square yard. High-design residential streets are generally only required in metropolitan areas. In these areas high standards are enforced so that roads will withstand the heavy traffic volume generally associated with dense urban residential development without necessitating heavy maintenance expenditures. These roads typically consist of a 4-inch crushed-stone subbase, a 6 to 8-inch asphaltic concrete base, and a 1½-inch asphalt surface. Based on bid figures provided by the City of Philadelphia, the cost of such streets varies from $4.75 to $6.10 per square yard.

Storm Sewers

Road storm sewers are required for almost all developments and urbanized areas. The design standards for such systems, and thus their cost, are, however, subject to considerable variation. High-design systems are generally installed in large-scale, new town developments and city residential areas. In high-design systems, inlets are spaced about every 200 feet along the road length with parallel storm drainpipes throughout. Double inlets are generally provided where residential streets join townwide roads. Data supplied by the City of Philadelphia, the New Communities division of HUD, the town of Columbia, Maryland, and the urban drainage district of Denver for a number of large residential developments indicate that high-design residential road sewer systems cost from $6.82 to $10.04 per front foot of building lot, or from $4.09 to $6.02 per square yard of surface area for a standard 30-foot wide residential street. In low-design systems, inlets are spaced further apart and the length of storm drainpipe is reduced. In very-low design systems, only one inlet is provided every few blocks and stormwater runoff is allowed to cross street intersections. Since inlet locations are designed to minimize the distance to existing trunk sewers or receiving water-courses, sewer pipes are not necessitated throughout the entire street length. The cost of such systems typically ranges from $1.80 to $3.00 per square yard of road surface.

Cost of Curbs and Gutters

Combined curbs and gutters are generally installed in new residential developments at a cost of from $2.50 to $4.00 per linear foot. For a 30-foot-wide residential road, curbs and gutters cost an additional $1.50 to $2.40 per square yard of surface area, which could be eliminated if porous pavements were used.

C. BUSINESS STREETS

Whereas suburban business streets are typically townwide roads designed to handle only a relatively moderate volume of traffic, city business streets must be designed to withstand greater traffic volumes. Since the design of business streets varies considerably with the expected traffic volume, city and suburban business streets are discussed separately below.

Pavement Design

Suburban business streets are typically constructed with a 6 to 7-inch crushed-stone base and a 2 to 2½-inch asphalt surface at a total cost of between $3.60 and $4.40 per square yard. To support considerable volumes of traffic, city business streets are generally constructed with a 6 to 10-inch concrete base, the thickness varying with the anticipated traffic volume, and a 2½-inch asphalt surface. Bid data supplied by the City of Philadelphia indicate a pavement cost of from $5.22 to $10.20 per square yard for these very-high-design roads.

Storm Sewers

Developers contacted indicated that the unit cost of storm-sewer systems for suburban business streets average from 20 to 25 percent higher than for high-design residential street systems. For a typical 40-foot-wide suburban business street, the average cost of storm drainage facilities would thus range from $3.30 to $5.50 per square yard of road surface. That the cost per square yard is less than for high-design residential systems is consistent with the fact that storm-sewer system costs do not increase proportionally with the increase in volume of surface runoff. In this instance, unlike city business streets, the increase in runoff is primarily due to the increase in road width rather than to increases in the extent of adjacent imprevious areas.

Data on the cost of road storm-sewer systems for city business streets were extremely difficult to obtain. Only one engineering firm was willing to provide an estimate of approximately $9.00 to $12.00 per square yard. This high cost is consistent with large increases in runoff from surrounding impervious areas and the normally closer spacing of storm inlets in city business areas.

D. COUNTY ROADS AND HIGHWAYS

The classification and design criteria for county roads and highways has been based largely on Pennsylvania Department of Highways specifications. Information from secondary sources and other state highway departments indicates that these specifications represent standard practice except in the case of low-level design county roads with traffic volumes of less than 800 cars per day. In most states, roads with an average daily traffic (ADT) of between 100 and 800 vehicles are designed to lower specifications than in Pennsylvania, and rural roads of less than 100 ADT are typically only treated gravel. Accordingly, the Pennsylvania classification system and design specifications have been adjusted to reflect lower standards in roads with 100 to 800 ADT; roads of less than 100 ADT, being generally unpaved, have been excluded from consideration.

Based on the above modifications, four county road classes have been been identified.

Road Class	Average Daily Traffic
Low-volume county road	100 to 800
Moderate-volume county road	800 to 2000
Two-lane highway	2000 to 10,000
Four-lane highway	above 10,000

Pavement Design

Design standards for county roads and highways by road class are indicated below:

Low-Volume County Road

Subbase: 6" (crushed stone or gravel)
Base: 4½" (bituminous concrete)
Surface: 1½" to 2½" (bituminous wearing and binder course)

Moderate-Volume County Road

Subbase: 8" to 12" (crushed stone or gravel)
Base: 5" to 6" (bituminous concrete, bituminous aggregate or cement aggregate)
Surface: 2½" (bituminous wearing and binder course)

Two-Lane Highway

Subbase: 8" to 15" (crushed stone or gravel)
Base: 5" to 6" (bituminous concrete, bituminous aggregate or cement aggregate)
Surface: 2½" to 4" (bituminous wearing and binder course)

Four-Lane Highway

Asphalt

Subbase: 8" to 16" (crushed stone or gravel)
Base: 7" to 10" (bituminous concrete, bituminous aggregate or cement aggregate
Surface: 3½" to 5" (bituminous wearing and binder course)

Concrete

Base: 8" to 12" (crushed stone, gravel or slag aggregate)
Surface: 8" to 10" (plain cement concrete or reinforced cement concrete)

Four-lane concrete highways are generally designed with surface and base only. However, in some states, particularly, a 4-inch cement-treated base and a thinner subbase are used. Cost for such construction is only slightly higher than for the above design.

The following total cost ranges have been calculated from a sample of bid sheets provided by the Pennsylvania Department of Highways. Since bids by contractors on the same work will vary by as much as 100 percent depending on the relative state of the industry, extremely high and low bids have been eliminated in arriving at these cost ranges. (Costs for individual road elements are detailed in Table 10.)

Type of Road	Pavement Cost ($\$/y^2$)
Low-volume county road	5.30 - 7.00
Moderate-volume county road	6.35 - 8.75
Two-lane highway	6.50 - 10.60
Four-lane highway	
Asphalt	8.60 - 12.50
Concrete	10.00 - 15.00

Storm Sewers

Three types of drainage systems are provided in county roads and highways: underdrain pipe to remove groundwater from the road base and prevent freeze-thaw damage, storm drainpipe to remove surface runoff, and culvert pipe to channel water under the roads where an existing stream or watercourse is intersected. Because culvert pipes would normally still have to be installed if porous pavement were used, the cost of culvert pipe installation has not been considered in this analysis.

The extent of surface and underdrainage facilities installed depends on the design level of the road itself. The higher the orginal design of the road (i.e., highway versus low-volume county road), the higher the level of drainage facilities provided because of the higher replacement cost of the road and because most higher design roads must meet federal specifications. (Most highways are funded through the Federal-Aid Primary or Interstate systems.) The frequency of inlet spacing between low-level county roads and highways typically differs by a factor of 10. Additionally, unlike small developments which tie into existing trunk sewer systems, major roads must provide their own capacity to the point of discharge. Where the distance to the discharge point is great, end-of-run pipes can reach over 72 inches in diameter, resulting in very heavy excavation and backfill costs. In large-scale residential and commercial developments, layouts are planned to avoid such excessive storm drainpipe costs. Further, within equivalent design classes, drainage provisions also vary as a result of difference in anticipated extent of runoff, road terrain, height of water table and anticipated amount of precipitation.

To arrive at reasonably representative cost figures, drainage costs including excavation and backfill for each county road and highway class have been calculated from a sample of construction bid figures provided by the Pennsylvania Department of Highways. These figures are representative for most of the country except for areas of extremely low or extremely high precipitation. In these areas, some adjustment would be necessary to reflect significant differences in size of storm drainpipes required to handle the anticipated volume of runoff. However, basic system design, which is the major determinant of drainage cost, is relatively uniform throughout the country. The

The relative insensitivity of systems design to annual precipitation is indicated, for example, by the fact that the residential storm drainage system design recommended for Columbia, Maryland, and Denver, Colorado, are essentially equivalent although the size of pipe required to handle anticipated runoff differs.

From the above Pennsylvania data, the following total drainage cost statistics (surface and underdrainage) per square yard of road surface have been calculated for county roads and highways.

Type of Road	Range ($\$/y^2$)	Weighted Average ($\$/y^2$)
Low-volume county road	0.68 - 4.27	1.27
Moderate-volume county road	2.15 - 6.43	3.43
Two-lane highway	2.04 - 9.85	5.95
Four-lane highway	7.76 - 18.90	13.33

Total Cost

Total average costs per square yard for pavement and drainage provisions on county roads and highways are indicated below:

Type of Road	Range ($\$/y^2$)	Weighted Average ($\$/y^2$)
Low-volume county road	5.98 - 11.27	7.42
Moderate-volume county road	8.50 - 15.18	10.98
Two-lane highway	8.54 - 20.45	14.50
Four-lane highway		
Asphalt	16.36 - 31.40	23.88
Concrete	17.76 - 33.90	25.83

Sidewalks

Basic sidewalk construction consists of a 2 to 4-inch gravel base and a 4-inch concrete surface. Occasionally, a 6-inch surface is used. Because of the small surface area and hand construction involved, costs per square yard of surface area are quite high, typically ranging from \$5.70 to \$8.05 per square yard. Drainage systems are not normally necessary.

E. PUBLIC SQUARES

Pavement Design

Public squares are normally constructed with a 4-inch gravel base and a 4 to 6-inch concrete surface, 6 inches generally being employed only where some vehicular traffic or other special factors are anticipated. Costs range from \$5.05 to \$6.55 per square yard.

Costs are relatively cheaper per unit than for sidewalks because of the larger average surface area and more mechanized construction, e.g., belt dragging rather than hand finishing.

Storm Sewers

The expected volume of storm runoff for public squares is essentially equal to that for parking lots. Storm drainage system design is thus equivalent to that for parking lots, with inlets normally spaced every 2000 square yards. Total system cost is somewhat lower, ranging from $0.90 to $1.20 per square yard of surface area, because proximity to existing street sewers reduces the length of storm drainpipe required.

F. PLAYGROUNDS

Information supplied by state and local recreation authorities indicates that playground design is relatively standardized. Most playgrounds are constructed with a 4-inch stone base and either a 2- or 2½-inch asphalt surface. Pavement costs for standard playgrounds range from $3.00 to $4.00 per square yard. Because of the smaller surface area of playgrounds, unit costs for equivalent designs are higher for playgrounds than for parking lots.

Storm Sewers

Costs of storm drainage facilities were estimated to range from $0.90 to $1.20 per square yard. Drainage provisions in urban areas are generally equivalent to those for public squares; standards in outlying areas are somewhat lower, but greater pipe footage is often required to connect with street storm-sewer lines.

G. AIRPORT RUNWAYS

Pavement Design

The design of major airport runways has been established for asphalt and concrete and is based on information from the Philadelphia International Airport, the Portland Cement Association and the Federal Aviation Administration's Bureau of Airports. Asphalt runways are typically constructed with a 3 to 12-inch crushed-stone subbase, a 7 to 12-inch bituminous penetration base, and a 4 to 6-inch asphalt surface. Variation in the thickness of construction materials depends both on the design level of the runway and the segment of the runway being considered, that is, the critical or non-critical portion of the runway. Major asphalt runway costs range from $8.00 to $12.90 per square yard of surface area.

Typical concrete runways for major airports consist of a 3 to 12-inch crushed-stone subbase, a 4 to 6-inch soil-cement base, and a 9 to 13-inch reinforced concrete surface. For concrete construction, subbases are generally limited to 3 inches unless greater thicknesses are necessary to prevent freeze-thaw damage. Costs for these runways are estimated at from $11.35 to $18.80 per square yard of surface area.

Storm Sewers

Runway storm drainage systems are constructed to avoid placing inlets in the runway surface itself. Accordingly, runways are generally sloped sufficiently to allow runoff to drain into inlets placed in ground areas bordering the runway. Cost statistics supplied by Philadelphia International Airport indicate that the total cost for such a system (subdrains, drainage structures and drainpipes) is $1,330,000, or $7.60 per square yard for a standard intercontinental runway 10,500 feet long and 150 feet wide.

H. SUMMARY OF CONVENTIONAL PAVEMENT COSTS

Pavement and drainage costs discussed in the text are summarized in Tables 10 through 12. Tables 10 and 11 give the range of cost estimates established for pavement and storm-sewer installation respectively. Average total costs for both pavement installation and drainage provisions are summarized in Table 12.

Table 10
CONVENTIONAL PAVEMENT CONSTRUCTION COSTS

Type of Pavement	Subbase		Base		Surface		Total
	$\$/y^2$	Thickness* (inches)	$\$/y^2$	Thickness* (inches)	$\$/y^2$	Thickness* (inches)	$\$/y^2$
Parking Lot	- - -		1.30 - 1.60	4 - 6	1.30 - 1.90	1½ - 2½	2.60 - 3.50
Residential Street							
Low-design			1.45 - 1.70	5 - 6	1.55 - 1.90	1½ - 2	3.00 - 3.60
High-design	1.00 - 1.40	4	2.75 - 3.45	6 - 8	1.00 - 1.25	1½	4.75 - 6.10
Business Street							
Suburban development			1.70 - 2.00	6 - 7	1.90 - 2.40	2 - 2½	3.60 - 4.40
City			3.77 - 8.20	6 - 10	1.50 - 2.00	2½	5.27 - 10.20
County Road							
Low-volume	1.80 - 2.00	6	2.40 - 3.00	4½	1.10 - 2.00	1½ - 2½	5.30 - 7.00
Moderate-volume	2.00 - 3.00	8 - 12	2.60 - 3.50	5 - 6	1.75 - 2.25	2½	6.35 - 8.75
Highway							
Two-lane	2.00 - 3.30	8 - 15	2.60 - 4.50	5 - 8	1.90 - 2.80	2½ - 4	6.50 - 10.60
Four-lane							
Asphalt	2.00 - 3.90	8 - 16	4.10 - 5.30	7 - 10	2.50 - 3.30	3½ - 5	8.60 - 12.50
Concrete	2.00 - 3.00	8 - 12	None		8.00 - 12.00	8 - 10	10.00 - 15.00
Sidewalk			0.75 - 1.05	2 - 4	4.95 - 7.00	4	5.70 - 8.05
Public Square			1.05	4	4.00 - 5.50	4 - 6	5.05 - 6.55
Playground			1.00 - 1.25	4	2.00 - 2.75	2 - 2½	3.00 - 4.00
Airport Runway							
Asphalt	1.15 - 3.00	3 - 12	4.10 - 6.10	7 - 12	2.75 - 3.80	4 - 6	8.00 - 12.90
Concrete	1.15 - 3.00	3 - 12	1.20 - 1.80	4 - 6	9.00 - 14.00	9 - 13	11.35 - 18.80

* Material indicated in text.

Table 11

DRAINAGE FACILITIES COSTS, INCLUDING INSTALLATION, EXCAVATION, AND BACKFILL

Type of Pavement	Surface ($\$/y^2$)	Underdrainage ($\$/y^2$)	Total ($\$/y^2$)
Parking Lot	1.05 - 2.06	0 - 0.15	1.05 - 2.21
Residential Street			
Low-design	1.80 - 6.02	— —	1.80 - 6.02
High-design	3.60 - 6.02	— —	3.60 - 6.02
Business Street			
Suburban development	3.30 - 5.50	— —	3.30 - 5.50
City	9.00 - 12.00	— —	9.00 - 12.00
County Road			
Low-volume	0.20 - 0.80	0.40 - 2.79	0.68 - 4.27*
Moderate-volume	0.96 - 4.12	0.26 - 0.97	2.15 - 6.43*
Highway			
Two-lane	0.94 - 6.76	0.65 - 1.13	2.04 - 9.85*
Four-lane	5.34 - 13.34	0.87 - 3.26	7.76 - 18.90*
Sidewalk	None	None	None
Public Square	0.90 - 1.20	— —	0.90 - 1.20
Playground	0.90 - 1.20	— —	0.90 - 1.20
Airport Runway	— —	— —	7.60

*Total includes costs of excavation and backfill which were not reported separately for surface and underdrain pipe installation.

Table 12

AVERAGE COSTS OF CONVENTIONAL PAVEMENT CONSTRUCTION

Type of Pavement	Pavement $(\$/y^2)$	Storm Drainage $(\$/y^2)$	Total Cost $(\$/y^2)$
Parking Lot	3.05	1.68	4.73
Residential Street			
Low-design	3.30	3.90	7.20
High-design	5.43	4.80	10.23
Business Street			
Suburban development	4.00	4.40	8.40
City	7.70	10.50	18.20
County Road			
Low-volume	6.15	1.27	7.42
Moderate-volume	7.55	3.43	10.98
Highway			
Two-lane	8.55	5.95	14.50
Four-lane			
Asphalt	10.55	13.33	23.88
Concrete	12.50	13.33	25.83
Sidewalk	6.88	None	6.88
Public Square	5.80	1.05	6.85
Playground	3.50	1.05	4.55
Airport Runway			
Asphalt	10.45	7.60	18.05
Concrete	15.08	7.60	22.68

SECTION XV

MAINTENANCE AND RESURFACING COSTS

Two aspects of recurring costs must be considered in assessing the economic feasibility of porous pavement: (1) the cost and required frequency of resurfacing and (2) the cost of routine annual maintenance. In characterizing costs between these two categories we have, with minor exception, followed the definition of the American Association of State Highway Officials which classifies surface treatment of less than three-quarters of an inch as maintenance, and of more than three-quarters of an inch as resurfacing.

A. COST AND FREQUENCY OF RESURFACING

Road Service Life

Data on resurfacing practices and the service life of original road surfaces--the time until the first resurfacing is required--have been obtained from a number of sources, 9-12 including city, state and private sources, and are summarized in Table 13. Because of their extremely low-level original design, parking lots generally require resurfacing after six years. Low-level design, flexible roads (low-design residential, business and county roads) have a service life of about 15 years, whereas high-level design, flexible surfaces last about 18 years and concrete roads about 26 years. Sidewalks and public squares require resurfacing after 20 years only if the pavement is eroded by snow and ice removal chemicals.

Resurfacing Practices

An asphalt overlay is almost universally used for resurfacing asphalt and concrete pavements. The thickness of the resurfacing layer normally varies between 1 and 3 inches (see Table 13), except for concrete runways where an average 4-inch overlay is used. As a rule, the thickness of the overlay varies linearly with the quality of the original road design. Thus a high-level design concrete road is generally given a 3-inch resurfacing, whereas low-level design residential streets may receive as little as a 1-inch overlay. For both sidewalks and public squares, resurfacing involves the complete removal and replacement of the original surface.

Resurfacing Cost

Total resurfacing costs, derived from secondary studies, are summarized in Table 13. Annual resurfacing costs have been derived on the basis of the length of time to first resurfacing and the interval between successive resurfacings evaluated over a 40-year period.[13]

Based on information from the California Highway study,[12] the time interval between resurfacings has been assumed to be 13 years for roadways. Resurfacing intervals for parking lots and playgrounds have

Table 13
SERVICE LIFE AND RESURFACING COSTS

Type of Pavement	Initial Service Life (years)	Resurfacing Thickness (inches)	Cost ($\$/y^2$)	Annual Cost[*] ($\$/y^2$)
Parking Lot	6	1 - 2	1.25 - 1.45	0.23 - 0.26[†]
Residential Street				
Low-design	15	1	1.10	0.08
High-design	17.5	2½	1.70	0.12
Business Street				
Suburban Development	15	1	1.10	0.08
City	17.5	2½	1.70	0.12
County Road				
Low-volume	15	1½	1.25	0.09
Moderate-volume	18	1½ - 2½	1.25 - 1.70	0.08 - 0.11
Highway				
Two-lane	18	1½ - 2½	1.25 - 1.70	0.08 - 0.11
Four-lane				
Asphalt	18	2½	1.70	0.08 - 0.11
Concrete	26	3	2.05	0.11
Sidewalk	20[‡]	4	6.15 - 8.20[δ]	0.31 - 0.41
Public Square	20[‡]	4 - 6	5.20 - 6.70[δ]	0.26 - 0.34
Playground	12.5	1	1.25	0.10
Airport Runway				
Asphalt	10	3	2.05	0.20
Concrete	15	4	2.45	0.21

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[*] A 40-year analysis period is generally recommended by highway engineers and has been adopted in this study. A uniform 13-year life is assumed for resurfacings.

[†] Includes costs of scarifying at fourth resurfacing.

[‡] Resurfacing necessary only where pavement is eroded by chemicals used in snow and ice control.

[δ] Includes cost of $\$1.20/y^2$ for removing old pavement.

been determined to be 6 years and 12.5 years, respectively. Sidewalks and public squares need replacement about every 20 years if eroded by snow and ice removal chemicals or otherwise damaged. By FAA standards, airport runways are designed for a 20-year life. Increasing traffic volumes and heavier jets have precluded this life expectancy from being realized. According to Philadelphia Airport engineers, the initial service life of airport runways is estimated at 10 years for asphalt construction and 15 years for concrete construction, with subsequent resurfacings required at 10-year intervals.

B. ANNUAL MAINTENANCE COST

Annual maintenance provisions considered in this report can be classified according to three major types of activities: (1) repairs to surface and base, (2) surface overlay treatments less than three-quarters of an inch thick and (3) repair and maintenance of drainage structures. Other maintenance activities such as control of roadside vegetation, snow and ice removal and repair of rest areas, although constituting a sizeable fraction of total maintenance costs, have not been considered because they are not relevant to the type of pavement surface. The three maintenance categories considered are described below, and costs for each type of pavement are given in the maintenance cost section.

Repairs to Surface and Base

Surface and base repair is occasioned primarily by four types of recurrent road defects: (1) potholes and chuckholes, (2) cracks and other minor varieties of surface disintegration, (3) edge curling and other edge damage and (4) pavement pumping. The first two types of surface damage occur because of inadequate base construction, poor drainage, and/or heavy traffic. Edge damage is typically encountered only in roads less than 24 feet wide where cars frequently travel over the edge. Pavement pumping occurs when concrete slabs are separated and base or subgrade materials are extruded through pavement joints.

Surface damage of the first three types is corrected by adding rolled asphalt with or without additional aggregate, depending on the depth of the damage. To prevent pavement pumping, concrete joints are generally sealed and waterproofed periodically. If pumping occurs, the pavement is packed with a mud slurry under the surface level and, if necessary, the base and slab are replaced.

Surface Treatment

Pavement surfaces become worn and smooth before they require complete replacement, thus increasing the danger of accidents and also exposing the underlying base materials. To correct this condition, pavements are periodically sealed with an asphalt coat, generally less than three-eighths of an inch thick, between the time of initial construction and resurfacing as well as between successive resurfacings.

Maintenance of Drainage Facilities

Maintenance of drainage facilities comprises the following activities: (1) repair of drainage structures such as inlets, manholes, and drainpipes (2) unclogging of storm inlets and (3) repair of drainage channels.

Maintenance Cost

In determining total maintenance cost, separate costs have been estimated for each of the three major maintenance activities above. The paucity of usable maintenance data has prohibited us from determining the quantity and unit cost of each maintenance activity as preferred. Rather, typical costs have been derived on the basis of reported maintenance cost experience for the three categories above. Because no one source provided adequate data to estimate costs for all pavement categories and maintenance types, data were obtained from several sources (including state and local officials and private contractors) which, in our opinion, reflect typical levels of maintenance activities.[14-17] The costs thus derived on the basis of direct labor, equipment and materials costs are summarized in Table 14, and the derivation of the cost figures for each pavement type is detailed in the paragraphs below.

Parking Lots

Information from local paving contractors indicates that annual surface and base maintenance, primarily pothole repair, requires the use of 75 to 100 tons of asphalt materials at an installed cost of $2250 to $3000 per year for a standard 50,000 square-yard parking area. On a square-yard basis, the annual surface and base maintenance cost is 4.4¢ to 6.0¢ per year. Because of their short service lives (6 years), parking lots are generally not given surface overlays between resurfacings. Drainage maintenance cost is judged insignificant. Most storm drainage systems are built with sufficient slope to achieve self-cleaning during storms. Consequently, open curb inlets only require cleaning when there is a large accumulation of debris. Street-level grated inlets such as used in parking lots and public squares clog much less frequently than curbed inlets. As a result, contractors indicate that parking lot inlets only need occasional cleaning.

Low-Design Residential Streets

Low-design residential streets are approximately equivalent in design to low-volume county roads. Accordingly, the cost of surface and base maintenance was estimated at 1.28¢ per square yard per year on the basis of National Cooperative Highway Research data[17] for a 30-foot road with an average daily traffic volume of 200. Data from the Pennsylvania Department of Highways established the cost of surface treatment (seal coating) at 15¢ per square yard. Estimated on the basis of an original 15-year service life, one surface treatment between resurfacings at 13-year intervals, and a 40-year analysis period, the average annual cost of

Table 14

ANNUAL MAINTENANCE COSTS

Type of Pavement	Surface & Base Repairs (¢/y^2)	Drainage Maintenance (¢/y^2)	Surface Treatment (Seal Cost) (¢/y^2)	Total Maintenance Cost (¢/y^2)
Parking Lot	4.40 - 6.00	Minimal	——	4.40 - 6.00
Residential Street				
Low-design	1.28	0.34	1.21	2.83
High-design	1.00	0.41	1.02	2.43
Business Street				
Suburban development	1.49 - 1.62	0.59	1.21	1.96 - 2.09
City	9.21	0.79	6.05*	16.05
County Road				
Low-volume	1.70 - 4.83	0.82	1.21	3.73 - 6.86
Moderate-volume	3.02	0.81	1.02	5.05
Highway				
Two-lane	3.02	0.88	1.02	4.92
Four-lane (very high design)				
Asphalt	4.21	0.36 - 1.05	1.02	5.59 - 6.28
Concrete	2.75	0.36 - 1.05	0.96	4.07 - 4.76
Sidewalk	——	——	——	——
Public Square	——	Minimal	——	——
Playground	0.37	Minimal	——	0.37
Airport				
Asphalt	4.21	Minimal	——	4.21
Concrete	2.75	Minimal	——	2.75

*Three-quarter-inch to one-inch asphalt overlay.

surface treatment is 1.21¢ per year. On the basis of the Virginia study,[14] the cost of drainage maintenance is estimated at 0.34¢ per square yard. This figure covers only the cost of cleaning and repairing drainage structures as opposed to maintenance for county roads and highways where considerable amount of drainage maintenance expenditure reflects the upkeep of drainage channels.

High-Design Residential Streets

Specific data on surface and base repair cost for high-design residential streets were not located. In view of the superior design of these streets, particularly the quality of the base, we have estimated the annual maintenance cost at 1.0¢ per square yard--somewhat lower than for low-design residential streets. Drainage maintenance cost was estimated from the Ohio survey[15] at 41¢ per square yard on the basis of cost data for local urban bituminous roads. Based on an original service life of 17.5 years and a 40-year analysis period, the cost of seal-coating was estimated to average 1.02¢ per square yard per year.

Suburban Business Streets

Surface and base maintenance was estimated at 1.49¢ to 1.62¢ per square yard per year, equivalent to the maintenance cost of a low-volume, 40-foot-wide county road with an average daily traffic of from 600 to 800 vehicles. Drainage maintenance cost was estimated from the Ohio study[15] at 0.59¢ per square yard per year on the basis of cost data for auxiliary rural bituminous roads. Cost for one surface treatment between resurfacings was estimated at 1.21¢ per square yard per year.

City Business Streets

Data on the cost of surface and base repairs for city business streets in Philadelphia was obtained from the Pennsylvania Department of Highways for fiscal years 1966 and 1967. Inflated to current price levels by the Federal Highway Administration's maintenance price index, the cost was estimated at $648.32 per lane mile or 9.21¢ per square yard per year. Data from the City of Philadelphia indicated that surface treatment consisted of a three-quarter-inch to one-inch overlay (rather than the thin layers generally used) at an average annual cost of 6.05¢ per square yard per year. Annual drainage maintenance cost was estimated from the Ohio study[15] at 0.79¢ for urban arterial bituminous streets.

Low-Volume County Roads

Annual surface and base repair cost was estimated from National Cooperative Highway Research data[17] at 1.70¢ to 4.83¢ per square yard for a 22-foot-wide road with ADT from 200 to 800 per day.

The higher cost than for residential and suburban business streets reflects the cost of repairing edge damage, a cost which is generally only significant for narrow, uncurbed roads. The range of maintenance costs reflects the tendency of edge repair costs to escalate more rapidly than other costs with increase in traffic volume. In the Virginia maintenance study,[14] Jorgensen and Associates estimated annual drainage maintenance costs at 1.82¢ per square yard of road surface. This cost reflects drainage-channel upkeep as well as drainage-structure cleaning and repair. Based on a 15-year initial life, surface treatment cost was estimated to average 1.21¢ per square yard per year.

Moderate-Volume County Roads

Surface and base repair costs, adjusted to current price levels, have been estimated at 3.02¢ per square yard on the basis of historical per lane mile maintenance costs for Pennsylvania high-design flexible roads. Drainage maintenance cost was estimated at 0.81¢ per yard using Jorgensen data. Based on an initial service life of 18 years, surface treatment was estimated to average 1.02¢ per square yard per year.

Two-Lane Highways

Surface and base repair costs for Pennsylvania high-design flexible roads were used to arrive at an estimated annual maintenance cost of 3.02¢ per square yard. Drainage maintenance costs based on the Virginia study data[14] were estimated at 0.88¢ per square yard. Surface treatment, 18-year initial life, was estimated to average 1.02¢ annually per square yard.

Four-Lane Highways

Pennsylvania maintenance data did not provide maintenance cost estimates for very-high-design four-lane highways. Surface and base repair costs were therefore estimated from the very comprehensive California highway maintenance cost study.[12] Adjusted to current price levels, surface and base repair costs from this source were estimated to average between 4.21¢ and 2.75¢ per square yard for asphalt and concrete construction, respectively. The higher maintenance cost for asphalt highways reflects the greater average durability of concrete construction. Annual drainage maintenance costs were estimated from Virginia maintenance data[14] to range from 0.36¢ to 1.05¢ per square yard. This wide range reflects the considerable maintenance economies realized where median-strip drainage is employed on divided four-lane highways. Surface treatment was estimated at 1.02¢ and 0.96¢ per square yard per year on the basis of 18 and 26-year service lives for asphalt and concrete highways, respectively.

Sidewalks

Surface repairs, other than replacement, and surface treatment are generally not made. Since drainage is typically into streets rather than through sidewalk inlets, no direct drainage maintenance cost is incurred.

Public Squares

Surface repair or surface treatment is not normally undertaken. Drainage maintenance cost was judged insignificant for the same reasons given under parking lots.

Playgrounds

Data from the Philadelphia and Pennsylvania Department of Recreation indicate that surface and base repair activity is very limited. Repair is generally restricted to one thorough patching job between resurfacings. On the basis of parking lot repair costs, such a patching job would cost 0.37¢ per square yard on an average annual basis. Surfaces are generally not treated between resurfacings. Since it is rarely necessary to clear a clogged inlet, drainage maintenance costs are insignificant.

Airport Runways

No specific cost data were available on surface and base repairs for airport runways. Contact with Philadelphia International Airport personnel indicated that maintenance activity was similar to highway repairs, consisting primarily of repairing potholes on asphalt runways and sealing and waterproofing joints on concrete runways. Consequently, maintenance cost for runways has been estimated to be equivalent to that for high-design highways: 4.21¢ and 2.75¢ per square yard, respectively, for asphalt and concrete. Regular surface treatments are not generally made on airport runways. Because of the infrequency of clogged inlets, drainage maintenance was judged insignificant.

C. SUMMARY OF MAINTENANCE AND RESURFACING COSTS

Total average maintenance costs and annual resurfacing costs are summarized in Table 15. The highest ratio of annual surface maintenance and resurfacing cost to total initial pavement cost is 7 percent for parking lots, largely because of their short initial service life. The ratio is less than 2 percent for all other pavements except playgrounds, public squares and sidewalks, and slightly less than 1 percent for highways.

Table 15
TOTAL ANNUAL MAINTENANCE AND RESURFACING COSTS

Type of Pavement	Annual Cost ($¢/y^2$)
Parking Lot	27.4 - 32.0
Residential Street	
Low-design	10.83
High-design	14.43
Business Street	
Suburban development	9.96 - 10.09
City	28.05
County Road	
Low-volume	12.73 - 15.86
Moderate-volume	13.05 - 16.05
Highway	
Two-lane	12.92 - 15.92
Four-lane	
Asphalt	13.57 - 17.28
Concrete	14.07 - 15.76
Sidewalk	0.31 - 0.41
Public Square	0.26 - 0.34
Playground	13.7
Airport Runway	
Asphalt	24.21
Concrete	23.75

SECTION XVI

POROUS PAVEMENT BENEFITS

Potential benefits from porous pavement, other than the savings in cost of storm drainage facilities discussed in Section XIV, are considered for three other areas: (1) relieving combined-sewer overflows, (2) augmenting water supplies, and (3) providing aesthetic and ecological benefits.

A. COMBINED-SEWER POLLUTION

Polluted overflows from combined sewer systems currently rank as one of the most significant and most difficult problems to solve in controlling pollution.

Overflow pollution arises during storms when the flow in combined sewer systems may be 100 to 200 times the amount of normal sewage flow. Because it is not economically feasible to design intercepting sewers and sewage treatment facilities to handle such flows, only a fraction of the combined flow can be intercepted and brought to a plant for treatment. The remainder, containing a mixture of sewage and stormwater, is discharged directly into rivers and streams.

In most combined systems, interceptor capacity generally ranges between only 1.5 to 4 times the average dry-weather flow, the low end of the range being typical of most older, large cities. Consequently, overflows generally occur when rainfalls as low as 0.02 to 0.04 inch per hour are recorded. Overflows have thus been known to average from 5 (Boston) to 16 (Toronto) times per month.

Although as little as 3 percent of the year's total sanitary wastewater production may be discharged untreated in stormwater overflows, as much as 25 to 40 percent of a year's production of suspended solids, putrescible organic matter and bacteria will be discharged untreated as a result of the tendency of these pollutants to settle at the bottom of sewers only to be picked up later and discharged with stormwater.

Overflows from combined sewers have consequently made the watercourses of numerous large cities unfit for public use, encouraged their eutrophication and rendered them aesthetically objectionable because of sludge deposits.[18]

Although at present combined sewer systems tend to be outlawed in new developments, they continue to exist in almost all of the larger cities, particularly in the Middle Atlantic, New England, and Great Lakes regions, and in many of their suburbs. It is estimated that approximately 18 percent of the U. S. population (36 million people) is served by combined sewers.[19]

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Present Solutions

Ignoring the need to treat storm waters, the most common method of dealing with overflow pollution is the complete separation of sanitary and storm-sewer systems. For economic reasons, the usual procedure is to build separate sanitary sewer systems parallel to the existing combined sewer lines. Such separation is becoming more common: In the 1963 to 1967 period, 1504 miles of combined sewers were separated compared to only 770 miles in the 1957 to 1962 period.[20] According to a recent American Public Works Association (APWA) survey, 71 percent of the 274 jurisdictions planning action to eliminate overflow pollution intend to proceed with complete sewer separation. Such separation is also required in all federally financed urban renewal projects.[21]

Although separation is universally recognized as the most effective solution, the cost is often prohibitive. According to the APWA, the cost of constructing a separate parallel system averages $10,200 per surface acre, and the cost of plumbing changes to affected buildings averages $6,000 per acre.[22] Significantly, the cost varies widely with population density as shown below. Costs are almost prohibitively high for those dense urban areas most in need of remedial action. The following cost data have been calculated on the basis of an average cost of $10,200 per acre for sewer separation and APWA's survey of engineering cost studies by size of community plus the per capita cost of plumbing changes times population density by size of community.

Size of Community	Cost per Acre
500 - 999	$ 1,511
1,000 - 4,999	2,568
5,000 - 9,999	3,151
10,000 - 24,999	4,629
25,000 - 49,999	6,434
50,000 - 99,999	6,411
100,000 - 499,999	12,682
500,000 and above	39,818

Despite such extreme costs, cities such as Washington, D.C., and Minneapolis, Minnesota, have embarked or intend to embark on complete separation of their sewer systems.

Most of the country's major cities, however, are investigating alternative approaches which, although not as effective as complete separation, are at least economically feasible. Such procedures include off-system storage, screening, chemical treatment, sedimentation ponds, and the installation of separate road sewer systems.

Based on the relatively small sample of available data, APWA estimates the cost of such alternative systems to average $5,100 per acre.[23] It is significant that the cost of such alternatives does not appear to vary as widely with the size of community.

Porous Pavement as an Alternative Solution

The construction of a separate system of road sewers is one of the alternative solutions to the combined-sewer problem adopted by Toronto and being considered by such other cities as Hamilton, Ontario and Buffalo, New York. In Toronto, overflow discharges had, by the late 1950's made all the city's watercourses too polluted to be used for recreational purposes. A 1960 study for the City of Toronto recommended that a separate road sewer system be constructed which would divert approximately 45 percent of the city's stormwater runoff and sufficiently curtail pollution from combined-sewer overflows to eventually render the city's waterfront suitable for public bathing.[24] The cost of this system was estimated at $7,000 per acre (60% less than the cost of complete sewer separation). Toronto has consequently adopted a 20-year program of separate road sewer construction which is currently in progress.

By its very nature, porous pavement would accomplish the same as construction of a separate road sewer system. It would also prevent runoff from roads--which is itself increasingly being viewed as a source of pollution[25] --from directly entering the watercourses. Given the fact that city streets have an average life of about 15 years, a program of replacing existing streets with porous pavement as their surfaces need replacement would relieve overflow from combined sewers in about the same period of time as the other methods of overflow control currently being adopted. There is thus obvious potential for the use of porous pavement as a water pollution control device.

Although the estimated cost of a separate road sewer system for Toronto was $7,000 per acre in 1960, the value of porous pavement as a means of combined sewer pollution control is probably most realistically figured at $5,100 per acre--the average cost per acre for all the alternative solutions surveyed in the APWA study.

Based on the 19-percent road-to-land-surface ratio (including parking lots) determined for Philadelphia,[26] the imputed economic worth of this use of porous pavement would be $5.54 per square yard for the estimated 18 percent of the country's roads located in communities served by combined sewer systems. The magnitude of the value of porous pavement for this particular use clearly makes it a potential worth considerable additional investigation.

B. WATER-SUPPLY DEFICIENCIES

Largely because the nation's population is becoming increasingly concentrated on a small fraction of its land and is expected to double by 2020,[27] the problem of providing adequate water to metropolitan areas has become of national significance and some urgency.

Inadequate water supplies are currently concentrated in two generalized areas of the country--the Southwest and the megalopolitan area of the eastern seaboard extending from Massachusetts to Virginia.

In the Southwest, moderate to severe water shortages exist in the California, Arkansas White-Red, Texas Gulf, Rio Grande, Upper Colorado, Lower Colorado, and Great Basin water resource regions. Together, these regions have a total population of 44,445,000. Not all areas within these regions, however, have water shortages, e.g., both northern California and eastern Texas have ample water supplies. No precise inventory of the affected population within these regions has been compiled; however, based on material from the Water Resources Council,[28] about 25.3 million persons or 57 percent of the total population of these regions reside in water-deficit areas.

Preliminary results from the Middle Atlantic Regional Water Resources study indicate that the following urbanized areas of the eastern seaboard have water-supply problems:[29] eastern Massachusetts, western Connecticut, Rhode Island, the New York-northwestern New Jersey consolidated metropolitan area, and the Washington, D.C., Standard Metropolitan Area. These areas have a total population of 22,210,000.

A total then of 47.5 million persons or 24 percent of the nation's population resides in areas of known water-supply shortages. Additionally, it is recognized that many smaller communities of which no inventory has been made have equivalent water-supply deficiencies.

Present Solutions

The transfer by pipeline of water from well-supplied river basins to insufficiently supplied basins is currently the most common method of overcoming water-supply imbalances. Such interbasin transfers are being made for distances of from 200 to 900 miles. Based on internal estimates, the fully amortized cost of such interbasin transfers ranges from 30¢ to 60¢ per 1000 gallons, depending on the distance involved. This range is consistent with cost estimates obtained for two water-transfer projects--the Canadian River project in Texas and the California State Water Plan in which water is being transferred from northern to southern California.

Porous Pavement as an Alternative Solution

In present practice, the use of storm-drainage systems in metropolitan areas channels stormwater runoff directly into rivers and other receiving watercourses, thereby generally preventing such runoff from augmenting municipal water supplies. By allowing precipitation to percolate back into the soil, the use of porous pavement would increase municipal water supplies. Benefits from porous pavement depend on four factors: (1) the average level of annual precipitation, (2) the amount of storm-water runoff, (3) the cost of alternative methods of augmenting water supply, and (4) the extent of the market demand for the additional water supply that could be provided by porous pavement.

In the east coast megalopolitan area where most of the affected population is concentrated, annual precipitation for the entire region averages approximately 42 inches. Almost all of the affected part of the Southwest lies in the 10 to 20-inch annual precipitation zone with an average annual rainfall of approximately 15 inches.

Since a certain amount of rainfall is absorbed or evaporates, the generally accepted 80-percent runoff factor has been adopted for assessing runoff from paved surfaces. After adjusting for the 80-percent runoff factor, each square year of porous pavement will increase groundwater supplies by 4.52 gallons per inch of precipitation. The 42-inch average rainfall in the Middle Atlantic States would thus yield about 190 gallons of water annually per square yard of paved surface. With water transfers costing from 30¢ to 60¢ per thousand gallons, the value of this increased water supply averages 8.55¢ per square yard, assuming a demand exists for all the additional water provided. After discounting at 6 percent over an average conventional road service life of 18 years, the total imputed volume is 93.1¢ per square yard of pavement. For service lives of 6, 12.5, 15, and 26 years, the total discounted value would be 42.3¢, 74.1¢, 83.5¢, and $1.12, respectively.

Similarly, the 15-inch average annual rainfall in the Southwest would yield about 68 gallons per square yard of paved surface with an annual value of 3.0¢ per year. Discounted over an average 18-year road life, the average total value is 32.5¢ per square yard of paved surface area. For service lives of 6, 12.5, 15, and 26 years, the discounted value would be 14.8¢, 25.9¢, 29.2¢, and 39.0¢, respectively.

A market demand for additional water sufficient to justify these imputed economic values seems assured from both increases in population and in per capita water use. On the basis of Philadelphia's road-to-land-area ratio of 19 percent, national current per capita water consumption and east coast precipitation rates, porous pavement would provide an increased water supply somewhat less than 9 percent over current demand levels. From Water Resource Council projections of increases in per capita water consumption and population growth, Middle Atlantic water demand should increase by 17.3 percent by 1980, more than sufficient to create a demand for the additional water supply. In the Southwest, which has lower precipitation and higher rates of population growth, the comparison would be even more favorable.

These porous pavement water-supply benefits are of considerable importance, since existing water transfer agreements can provide only a temporary solution to the water-supply problem. Despite existing water transfers from the Upper Colorado, the Lower Colorado region still has a water shortage problem. Further, current projections indicate that water transfers will not be adequate to supply southern California's demands after 1990. Although it is expected that desalination will be able to produce water at 20¢ per thousand gallons by 1990,[27] such water will still have to be pipelined from coastal areas. Considerable potential thus exists for porous pavement to supplement other methods of water-supply augmentation.

C. AESTHETIC AND ECOLOGICAL BENEFITS

In addition to relieving flash flooding and increasing municipal water supplies, several other categories of less general but nevertheless significant possible benefits from porous pavement have been identified. Primary among these are the aesthetic and temperature benefits of color infusion and the ecological benefits associated with relief from flash flooding and preservation of normal drainage patterns.

Color Infusion

From conversations with government and business planners, it was evident that there will be a considerable demand for color-infused porous paving surfaces, particularly in the areas of traffic control, aesthetic improvement and temperature control.

Directional Control

Color-infused surfaces for traffic control are important in three types of paved surfaces: office parking lots, highways, and playgrounds. Several developers indicated that variegated color-coding of office parking areas would be extremely valuable. Such coding would delimit reserved parking areas much more effectively than the signs and imprinted bollards now in use. Similarly, officials of city and state recreation departments identified a demand for variegated coloring on playground surfaces. Color coding would increase safety by delimiting areas of high activity, such as around swings and other apparatus, from general play areas.

Two areas of highway traffic control were indicated as important uses for color-infused pavement--deceleration control lanes and highway routing. Highway safety would be considerably improved if deceleration lanes from high-speed county highways into residential and suburban business areas were clearly indicated by uniform color-coded surfaces. At present, deceleration areas are heavily posted--a technique which is not only expensive but also less psychologically effective than uniform color-coding. Highway officials also expressed considerable interest in color-coded surfaces for highway directional routing. By providing extremely explicit directional aid, a color-coded routing system would decrease accidents caused by th abrupt lane switching of drivers who had missed, misread, or misinterpreted posted signs. Highway color-coding has been tried in numerous parts of the country but has been unsuccessful primarily because of the short life of presently available color overlays and the lack of a uniform national color code. If a durable colored surface could be developed it would doubtless have a considerable market among state highway departments.

Aesthetic Enchancement

Aesthetic considerations dictate a demand for color infusion in three types of pavement: residential streets, specialized recreation areas, and parks.

Conversations with a number of developers and urban designers indicate a preference for paving residential streets in quiet earth tones which would blend with the natural environment and provide a more restful setting than is currently possible with the starkly unnatural contrast provided by blacktop. It is evident that there would be considerable demand for such color-infused surfaces if they could be produced at a competitive cost.

Park officials expressed an equal enthusiasm for using color-infused asphalt surfaces. Officials of the National Park Service were especially interested in such surfaces because they are committed to attempting to eliminate blacktop roads from the National Parks and have actively tested various color overlays without finding any of them sufficiently durable.

Acrylic color overlays are currently used in specialized recreation areas, such as tennis courts where surface wear is not a problem, to provide a more attractive surface. Color-infused porous pavement would be desired for aesthetic reasons if it could be produced at a competitive price.

Temperature Control

The use of colored asphalt for temperature control was judged by urban planners as being particularly valuable for use in dense residential areas, particularly inner-city urban-renewal districts. The placement of light tan pavements in urban-renewal areas would eliminate the unpleasant heat absorption effects of blacktop surfaces as well as provide a cooler and more restful appearance.

Removal of Curbing

The elimination of curbing was initially expected to be one of the major aesthetic benefits to be obtained from porous pavement.

The opinions expressed by developers and architects on the aesthetic value of eliminating curbing were, however, rather mixed. Some saw it as an aesthetic improvement and others viewed it as a rather neutral development, possibly because they have become so accustomed to viewing it as an integral part of residential developments. In almost all cases, it was felt that public safety dictated that curbing should only be eliminated in low-speed, low-traffic residential areas.

Despite the fact that no clear-cut aesthetic benefit was found, the elimination of the necessity for curbs and gutters to channel water to storm inlets would provide a considerable cost savings of from $2.50 to $4.00 per linear foot of building lot frontage.

Specialized Surfaces

As a result of our analysis of the cost of conventional pavement surfaces, it was decided that, in most instances, exotic porous paving surfaces, such as perforated butyl rubber sheets and modified carpeting, would not be economically feasible. Only one area of significant potential for such surfaces was evidenced--safety areas under playground apparatus. Specialized materials, such as woodchips, rubberized materials, and special carpetings, have been used experimentally in such areas. The cost of these experimental materials has sometimes exceeded $10 per square yard. However, prevailing opinion indicates that a cost no higher than $5 to $6 per square yard and relatively good wear characteristics would be necessary for general use in safety areas under playground apparatus. In general, it is questionable whether the limited market demand for exotic surfacing materials would justify their development and production.

Ecological Benefits

Several ecological benefits were identified primarily involving relief from flash flooding and the preservation of normal drainage patterns as well as, to a more limited extent, the preservation of roadside vegetation.

Relief From Flash Flooding

In outlying suburban areas, storm runoff from large paved surfaces, primarily parking areas, is outflowed through storm drains directly into the nearest stream or other adjacent watercourse. This practice produces considerable flash flooding and stream-bed erosion during periods of heavy rainfall. Demand for porous pavement to eliminate flash flooding is probably limited at present since most flash flooding results from private developments. In some areas, for example in Springfield Township, Pennsylvania, action has been taken to protect streams by forcing developers to control release of runoff. Greater restrictions are anticipated from increased public ecological awareness and should create a natural market for porous pavement.

Preservation of Natural Drainage Patterns

Impervious paved surface have the detrimental effect of interrupting natural drainage patterns. Disturbance of natural drainage patterns is undesirable where paving is imposed on otherwise open areas whose natural character is worth preserving and/or areas where the surfacing will only be temporary. Our investigations indicate that quasi-public organizations which have large areas of parking on scenic open land are actively searching for paving surfaces which would preserve the natural drainage pattern as well as prevent spoilation of streams through flash flooding. Additionally, representatives of the City of Philadelphia have expressed considerable interest in the use of porous pavement for the parking areas at the Bicentennial Exposition so that the land can later be returned to its original state. It is anticipated, of course, that the market for porous pavement for this use would be largely limited to public and quasi-public authorities.

Preservation of Roadside Vegetation

Only very limited demand was evidenced for the use of porous pavement to prevent water starvation of roadside vegetation. It was generally agreed that roadside vegetation does not suffer water starvation in single-family, residential, and other low-density developments. The only areas where it was generally felt that roadside vegetation was sufficiently water-starved for porous pavement to be beneficial were urban parks in large cities, paved areas in hi-rise apartment clusters, dense urban areas where little exposed ground exists, and large paved surfaces where plantings may be desired.

Economic Evaluation of Aesthetic and Ecological Benefits

In most cases it has not been possible to rigorously establish the economic value of the aesthetic and ecological benefits identified since alternatives to obtaining these benefits from other sources are not currently in use. Accordingly, the government and private officials who identified the various benefits were asked to evaluate them in terms of the premium they would pay to obtain them. In most cases, the market value placed on the benefits was relatively modest. Typical premiums estimated for the various benefits are enumerated in Table 16. In some cases, values were not assigned because the particular benefit would require governmental and/or legislative action to create a market demand. In general, premiums for certain specialized uses such as parking lot and playground color infusion are relatively high, whereas for more general uses, such as color-infused residential streets, the assessed value of the benefits is low in relation to the total pavement cost.

Table 16

ECONOMIC EVALUATION: AESTHETIC AND ECOLOGICAL BENEFITS

Category	Type of Benefit	Type of Pavement	Economic Value
Color Infusion	Aesthetic	Residential streets	10% of current pavement cost
	Aesthetic	Park roads	10-25% of current pavement cost
	Aesthetic	Specialized recreation surfaces (primarily tennis courts)	$\$2/y^2$[*]
	Traffic control	Suburban business streets (deceleration lanes)	$\$1$ to $\$1.50/y^2$
		Highways (routing)	$\$2.25$ to $\$3.50/y^2$[†]
		Parking lots	$\$1/y^2$
		Playgrounds	$\$1$ to $\$2/y^2$
	Temperature control	Inner-city residential streets (primarily urban renewal)	No value assigned. Must be incorporated into bid specifications.
Removal of Curbing	Aesthetic	Residential streets	$\$1.50$ to $\$2.40/y^2$[‡]
Environmental	Relief from flash flooding	Large parking surfaces	No value assigned. Demand must be legislated.
	Preservation of natural drainage	Large parking surfaces	$\$1$ to $\$2/y^2$ in very limited uses
	Preservation of roadside vegetation	Roads in dense urban areas	$\$0.50$ to $\$1.00/y^2$[δ]

[*] Based on current cost of installed acrylic surfaces for tennis courts.

[†] Based on current cost of experimental color overlays per *Engineering News Record*, Dec. 14, 1967, pp. 41-43.

[‡] Based on current cost of \$2.50 to \$4.00 per linear foot for combined curb and gutter for standard 30-foot-wide residential street.

[δ] Higher in those very limited uses where it is desired to preserve extremely old or valuable trees.

It was repeatedly emphasized throughout this study, however, that in order for these premiums to be sustainable, it is absolutely essential that the pavement require no more maintenance effort than current surfaces. As most public officials observed, it's a lot easier to get money to build roads than to maintain them. It is precisely these increased maintenance costs that have prevented colored asphalt overlays from coming into general use.

Additionally, particularly in the residential sector, a significant extra premium could be obtained if a porous pavement material could be designed capable of being laid during the winter. Current asphalt surfaces must be laid when the temperature of the surface is 50°F or higher. This limitation means that road surfaces must be laid during the summer and that most fully developed building lots thus have to be carried to the following spring/summer selling season. Carrying costs of $250 to $400 per building lot, or $1 to $1.25 per square yard of road surface, would be eliminated if road surfaces could be laid during the winter.

SECTION XVII

MARKET DEMAND FOR POROUS PAVEMENT

The market demand for porous pavement has been assessed in three phases: (1) the total annual pavement demand for the types of pavement under consideration has been estimated, (2) the cost of porous pavements of equivalent design has been assessed and (3) the total annual pavement demand, cost of conventional pavement surfaces, imputed premiums for specialized porous pavement benefits, and the cost of porous pavements for designs equivalent to conventional surfaces have been related to determine the potential market demand for porous pavement at various price levels.

A. CONVENTIONAL PAVEMENT DEMAND

Estimates of conventional pavement demand by pavement type have been derived from a number of primary and secondary sources. An attempt has been made to arrive at as comprehensive estimates as possible; however, because of the lack of comprehensive data sources, it has not been possible to include minor sources of demand in all categories. Derivation of demand estimates for each pavement type is discussed in the paragraphs below, and these estimates are summarized in Table 17.

Parking Lots

Pavement demand estimates for parking lots have been based on the three major users of surface parking lots: shopping centers, office buildings and industrial plants. On the basis of the National Parking Association's estimate that 500 shopping centers are constructed annually with an average parking area of 50,000 square yards, the annual demand for shopping center parking surfaces has been estimated at 25 million square yards.

Demand for industrial plant parking lots has been estimated to average 11.6 million square yards per year on the basis of the annual increase in manufacturing employment, 1960-1969, and an Institute of Traffic Engineers' survey of the ratio of parking spaces to number of employees in manufacturing industries.[30]

Demand for office parking lots has been estimated on the basis of new suburban office parking demand since most city office buildings rely on parking structures rather than street-level parking. Demand for suburban office parking spaces is estimated to grow by 1.45 million in the next six years,[31] implying an annual street-level parking demand of approximately 9.4 million square yards.

Total annual demand for large parking areas, based on the three major use categories, was thus estimated at about 46 million square yards.

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Residential Streets

The total volume of residential street construction has been estimated on the basis of the annual level of single-family housing construction and the average lot frontage of single-family dwellings. On the basis of recent statistics, total housing starts for 1971 are estimated at 1.8 million. Of these units, 59.7 percent are planned as single-family residences and approximately 15 percent as townhouses.[32] Lot front footage was estimated at 90 feet for detached single-family residences and 31.6 feet for townhouses.[33] Assuming a standard 30-foot-wide residential street, this level of housing construction implies construction of 8270 miles of residential roads or approximately 145.6 million square yards of residential street surfaces.

The total estimated residential street construction has been segregated into demand by design level on the basis of the location of construction: non-SMSA (Standard Metropolitan Statistical Area), suburban county within SMSA, and metropolitan city.

Recent housing construction data were available for 40 of the country's 115 major SMSA's. On the basis of extrapolation by population, 68.5 percent of residential construction is estimated to be within SMSA's and 31.5 percent in non-SMSA's.[34] Based on Philadelphia's housing data, 12.1 percent of SMSA construction is estimated to be located within central cities. Annual housing starts are thus estimated as follows: 8.33 percent in metropolitan areas, 60.14 percent in suburban SMSA counties and 31.53 percent in non-SMSA counties.

These statistics imply annual residential road construction of 689 miles in metropolitan cities where high design standards prevail, 4974 miles in suburban SMSA counties where the upper end of the low-design range (8 or more inches total thickness) is generally observed and 2607 miles in non-SMSA counties where the lower level of low-design construction (less than 8 inches total thickness) is generally observed.

Business Streets

Estimates of the annual volume of business street construction were based on the standard developers' total road construction breakdown of 85 percent residential streets and 15 percent business streets. Based on this ratio, a total annual construction of 1458.7 miles of business streets associated with single-family residences and 984.6 miles associated with apartment dwelling units was estimated. Of this total, 8.33 percent, or 203.6 miles, was estimated to be city business streets on the basis of the construction location data given in the previous sections. Assuming a standard 40-foot-wide business road, a total demand of 57.3 million square yards was estimated: 4.8 million in metropolitan areas and 52.5 million outside metropolitan areas.

County Roads and Highways

Data on the total level of county road and highway construction were obtained for 1969 from the U.S. Department of Transportation.[35] In most instances, the distribution of average daily traffic (ADT) volumes was not available from which to segregate total construction into the four general ADT classes identified in this study. Construction estimates for these four road classifications were therefore interpolated using data on the design level of existing roads[35] and the ADT data that was available for the primary system. In making these estimates, the following road systems were considered: rural primary and secondary roads, secondary and primary municipal extensions, interstate highways and local and forest roads.

Low-Volume County Roads

Low-volume road construction on the primary road system was estimated on the basis of ADT data for existing primary mileage. Low-volume road construction on other road systems was estimated by assigning a percent of new construction to this sector equal to the existing percent of low-design roads on each system.

Moderate-Volume County Roads

The annual construction of moderate-volume roads was estimated from total road construction on the basis of the percent of roads with ADT volumes of 800 to 2000 on the primary road system. For other road systems, this ratio was adjusted on the basis of the variation in the distribution of design levels of existing roads for each road system.

Highways

The remaining constructed mileage of moderately-high-level-design and high-level-design roads was segregated between two and four-lane highways on the basis of the distribution of roads by width on the primary system. For other road systems, adjustments to this ratio were interpolated on the basis of differences in the distribution of moderately high-level-design and high-level-design roads for each road system.

From the above data analysis, the following annual road-construction estimates were derived:

Low-volume county roads	15,009 miles
Moderate-volume county roads	14,479 miles
Two-lane highways	10,082 miles
Four-lane highways	3,694 miles

Based on average widths of 22 feet for low-volume roads, 24 feet for moderate-volume roads and two-lane highways, and 48 feet for four-lane highways, the following annual pavement demand levels were estimated:

Low-volume county roads	193.6 million square yards
Moderate-volume county roads	203.9 million square yards
Two-lane highways	141.9 million square yards
Four-lane highways	104.0 million square yards

Sidewalks

Sidewalks are primarily provided with residential streets, business streets and the municipal extensions of primary and secondary highways. Total annual construction of these roads (based on data from previous sections and Reference[35] is estimated at 14,113 miles, implying an annual construction of 28,226 miles of sidewalks or 66.9 million square yards of standard 4-foot-wide sidewalks.

Playgrounds

Paved playground areas are generally constructed with or associated with school construction. Paved playground areas recommended in a 1969 School District of Philadelphia study[36] are 0.24 acres for elementary schools and 0.68 acres for junior and senior high schools. Elementary and secondary school construction estimated on the basis of pupil growth from 1968 to 1970 and the average number of pupils per school[37] indicates an annual demand for paved playgrounds of 833 acres or approximately 4.4 million square yards.

Public Squares

Relatively precise data from which to estimate public square construction was not available. Accordingly, we assumed a construction level of one public square per year for each of the country's 115 major metropolitan areas and for each of the approximate annual total of 40 new residential developments exceeding 1000 homes. Assuming a representative plaza size of 15.5 thousand square yards, the total pavement demand would be approximately 2.4 million square yards per year.

Airport Runways

Based on data from the Portland Cement Association, it was estimated that major private airport runway construction (FAA continental and intercontinental standards) averages about nine runways per year. A total pavement demand of approximately 1.5 million square yard is thus indicated for a standard runway measuring 10,000 feet in length and averaging 150 feet in width. Total runway construction was estimated to be approximately 25 percent asphalt and 75 percent concrete.

Demand Summary

Total annual demand for pavement surfaces, estimated as above, for each pavement category are summarized in Table 17.

Table 17
PAVEMENT DEMAND ESTIMATES

Type of Pavement	Miles	Surface Area (Thousand Sq. Yds.)
Parking Lot	----	45,986
Residential Street*		
Low-design: SMSA	4,974	87,538
Non-SMSA	2,607	45,887
High-design	689	12,129
Business Street		
Suburban development	2,240	52,547
City†	204	4,776
County Road		
Low-volume	15,009	193,628
Moderate-volume	14,479	203,864
Highway		
Two-lane	10,082	141,955
Four-lane	3,694	104,023
Sidewalk	----	66,926
Public Square	----	2,400
Playground	----	4,397
Major Airport Runway	----	1,500‡

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* Width assumptions used in making these calculations are residential street, 30 ft.; business street, 40 ft.; low-volume road, 22 ft.; moderate-volume road, 24 ft.; two-lane highway, 24 ft.; and four-lane highway, 48 ft.

† Includes only city business streets associated with expanded residential/commercial development. Major city traffic arteries are included under highways.

‡ Estimated construction breakdown: asphalt, 25%; concrete 75%.

B. COMPARISON OF CONVENTIONAL PAVEMENT WITH POROUS PAVEMENT

Porous pavements have been designed for various levels of traffic volume on the basis of Asphalt Institute of America and California State Highway Department specifications. In establishing these designs, two basic assumptions have been adopted: (1) design thicknesses are based on the assumption of a poor subgrade to allow for the low load-bearing capacity of wet subgrades and (2) a minimum 16-inch crushed-stone base has been adopted in all pavement designs to provide sufficient base reservoir capacity to handle a 5.4-inch maximum daily precipitation. On non-clay soils (permeability ≥ 0.04), a maximum of ten days would be required for this level of precipitation to percolate into the subsurface soil.

Porous pavements designed to the above specifications are classified in Table 19 on the basis of design traffic number (DTN): DTN values below 100 represent low and moderate traffic volumes; DTN readings between 100 and 5000 indicate heavy traffic flows. A complete description of the derivation of porous pavement design by DTN classification is given in the portion of this study on physical design.

Table 18

POROUS PAVEMENT DESIGN BY DESIGN TRAFFIC NUMBER

Design Traffic Number	Crushed-Stone Base (inches)	Asphalt Concrete Surface (inches)
1	16	4
10	16	4
20	16	4½
50	16	5
100	16	5
1000	20	6
5000	22	7

These DTN classifications have been used to establish equivalent porous pavement designs for each of the conventional types of pavement considered in preceding sections. Table 19 gives the DTN classifications and equivalent porous design for each of the major types of road. In constructing this table, several exceptions to the original pavement classification have been made. Public squares and sidewalks have been omitted because the surface qualities of porous asphalt concrete were not considered aesthetically suitable in this use. Because of the relatively small difference in porous design, low-volume and moderate-volume county roads have been combined. Further, airport runways have not been considered in this comparison because the design specifications adopted could not be used to establish porous runway designs.

Table 19

EQUIVALENT POROUS PAVEMENT DESIGN

Type of Pavement	DTN	Crushed-Stone Base (inches)	Asphalt Concrete Surface (inches)
Parking Lot	1-10	16	4
Residential Street			
Low-design	1-10	16	4
High-design	10-20	16	4-4½
Business Street			
Suburban development	20-100	16	4½-5
City	100-1000	16-20	5-6
County Road	10-100	16	4-5
Highway			
Two-lane	100-1000	16-20	5-6
Four-lane	1000-5000	20-22	6-7
Playground	1	16	4

Costs for the above porous pavement designs have been estimated from secondary sources (see Reference 8). In addition to the cost of surface and base, $1.00 per cubic yard has been allowed for excess excavation where the total thickness of the porous design exceeds that of the conventional pavement design. Costs of these porous designs are compared with the cost of conventional pavements and storm sewers in Table 20.

Largely because of the need to install a 16-inch base reservoir capacity, the cost of porous pavement exceeds conventional pavement costs for most parking lots and playgrounds and many low-level-design residential streets. For the remaining higher design uses, porous pavement offers a cost advantage over standard pavements with storm drainage installations.

The cost economies are most significant for the very highest uses--city business and residential streets and highways where the conventional pavement thickness approaches that of the porous design and where extensive storm-sewer installations are typically provided.

C. MARKET DEMAND AND PRICE SUMMARY

The results of the investigations reported in the preceding sections are summarized in Table 21 which indicates gross annual pavement demand, the comparative cost of porous and conventional surfaces, the dollar value of porous pavement benefits and the percent of gross demand to which these premiums would apply.

Table 20

COST COMPARISON OF POROUS PAVEMENT AND CONVENTIONAL PAVEMENT WITH STORM DRAINAGE

Type of Pavement	Porous Pavement		Conventional Pavement	
	Cost Range ($\$/y^2$)	Average Cost ($\$/y^2$)	Cost Range ($\$/y^2$)	Average Cost ($\$/y^2$)
Parking Lot	6.32 - 6.40*	6.36	3.65 - 5.81	4.73
Residential Street				
Low-design	6.33 - 6.37*	6.35	4.80 - 9.60	7.20
High-design	6.19 - 6.56	6.38	8.35 - 12.10	10.23
Business Street				
Suburban development	6.65 - 6.99	6.38	6.90 - 9.90	8.40
City	6.99 - 8.32	7.66	14.20 - 22.20	18.20
County Road	6.01 - 6.87	6.44	7.24 - 13.23	9.20
Highway				
Two-lane	6.80 - 7.92	7.36	8.54 - 20.45	14.50
Four-lane				
Asphalt	8.16 - 8.79	8.48	16.36 - 31.40	23.88
Concrete	8.23 - 9.04	8.64	17.76 - 33.90	25.83
Playground	4.35 - 4.36*	4.36	3.90 - 5.20	4.55

*Range reflects differences in excavation costs.

Table 21

POROUS PAVEMENT BENEFITS

Type of Pavement	Annual Demand (1000 y^2)	Conventional Pavement with Drainage ($\$/y^2$)	Porous Pavement ($\$/y^2$)	Combined-Sewer Relief		Water Supply		Color Infusion	
				Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)
Parking Lot	45,986	4.73	6.36	18	5.54	24	0.15 - 0.42	20	1.00
Residential Street									
Low-design	133,425	7.20	6.35	18	5.54	24	0.29 - 0.83	40	0.30 - 0.40
High-design	12,129	10.23	6.38	18	5.54	24	0.32 - 0.92	10 - 25	1.00
Business Street									
Suburban Development	52,547	8.40	6.38	18	5.54	24	0.29 - 0.83	<5	1.00 - 1.50
City	4,776	18.20	7.66	18	5.54	24	0.32 - 0.83		
County Road									
Low-volume	193,628	9.20	6.44	18	5.54	24	0.29 - 0.83	<5	0.50 - 1.75
Moderate-volume	203,864				5.54	24	0.33 - 0.84		
Highway									
Two-lane	141,955	14.50	7.36	18	5.54	24	0.33 - 0.84		
Four-lane									
Asphalt	104,023	23.88	8.48	18	5.54	24	0.33 - 0.84	[5 - 10	2.50 - 3.50]
Concrete		25.83	8.64	18	5.54	24	0.39 - 1.12		
Playground	4,397	4.55	6.34					80	1.00 - 2.20

Table 21 (Cont.)

POROUS PAVEMENT BENEFITS

Type of Pavement	Natural Drainage Preservation and Flash Flood Relief		Preservation of Vegetation		Elimination of Curbing	
	Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)	Gross Demand Affected (%)	Added Value ($\$/y^2$)
Parking Lot	<5	1.00 - 200	<5	0.50 - 1.00		
Residential Street						
Low-design			<5	0.50 - 1.00	85	1.50 - 2.40
High-design			10 - 25	0.50 - 1.00	50	1.50 - 2.40
Business Street						
Suburban Development						
City						
County Road						
Low-volume			<5	0.50 - 1.00		
Moderate-volume						
Highway						
Two-lane						
Four-lane						
Asphalt						
Concrete						
Playground						

On a strict cost-comparison basis, which does not take into account any of its environmental and safety benefits, porous pavement has the potential in all uses, except parking lots, low-design residential streets and playgrounds, of eventually approaching a market equal to the indicated gross annual demand subject to the following qualifications:

1. The pavement designs from which these cost comparisons have been made assume construction over non-clay soils (permeability ≥ 0.04). The potential market demand will be reduced to the extent that road construction occurs over clay soils although no reliable figures are available upon which to estimate this extent. Test borings will be required as each road site to evaluate the soil's suitability for porous pavement.

2. Cost comparisons have been made on the basis of average Middle Atlantic precipitation. In areas of very high precipitation, a deeper, more expensive reservoir capacity would be required unless the subgrade has a very high percolation rate. Correspondingly, in areas of low precipitation and/or high percolation, a cheaper porous design could be used.

3. For these cost comparisons to be valid, porous pavement maintenance costs must not significantly exceed those of conventional pavements. Since porous pavement design uses current road construction materials (asphalt concrete and crushed stone), it has been assumed that maintenance costs would approximate present levels. For porous pavement to realize its market potential, satisfactory maintenance experience would have to be experimentally demonstrated.

4. The potential indicated could only occur over a substantial period of time as the feasibility of porous pavement is demonstrated in use. No basis exists from which to satisfactorily gauge the speed of acceptance.

For the remaining pavement types the potential market is smaller. Porous pavement parking lots and playgrounds are only cost competitive where soil or precipitation conditions are more favorable than those conditions on which our cost comparisons were based. Similarly, on the basis of our average cost range, porous pavement would be cost competitive for only about one-half of the low-level-design residential streets. In many cases, however, porous pavement would be economically feasible in these uses on the basis of the value of additional benefits obtainable from porous pavements. These benefits and their markets are discussed below.

The value of applicable porous pavements benefits and their relative demand are indicated in Table 21. These benefits are enumerated separately although, in many cases, part of the demand for one benefit will intersect with the demand for other benefits, implying a correspondingly greater total benefit premium for porous pavement.

The most significant benefit identified is the relief from combined-sewer pollution. As shown in Section XVI, this benefit would add an estimated value of $5.54 per square yard affecting approximately 18 percent of the total pavement market. The imputed value of this benefit is not, however, realizable in the private market, but is realistic only if a public program were initiated to utilize porous pavement to relieve combined-sewer pollution.

Based on the present distribution of water-supply deficiencies, porous pavement could command a premium value as a means of water-supply augmentation in 24 percent of the total market for paved roads and parking surfaces. The imputed premium for this benefit varies from $0.15 to $1.12 per square yard of surface area, depending on the service life of the paved structure and the level of precipitation in the area of installation.

The demand for colored parking surfaces is estimated at 20 percent of the total parking lot market, equal to the percent of the total parking area demand represented by street-level office parking lots where the demand for colored surfaces is extremely strong. According to industry representatives, a variegated colored surface would command a premium of $1.00 per square yard.

It is estimated that 40 percent of the market for low-design residential streets would consist of colored surfaces if they could be obtained at a 10-percent premium over present costs, or about 30¢ to 40¢ per square yard. The demand for colored streets is almost exclusively for use in large-scale developments. Little demand is evidenced for scattered residential developments where the overall aesthetic effect would be minimized by large surrounding areas of blacktop.

Public authorities would constitute the prime market for colored, high-level-design city residential streets. The remaining city residential construction is generally concentrated in smaller, scattered developments where the demand for colored surfaces is not strong. Accordingly, color-infused surfaces would command between 10 and 25 percent of the city residential street market, depending on the level of urban renewal and public housing activities. Although no exact determination was available from public officials, the combination of aesthetic and temperature-control benefits from colored surfaces should reasonably be expected to command a premium of $1.00 per square yard.

Colored surfaces for suburban business streets are demanded primarily for deceleration lanes and would command less than 5 percent of the total market. Developers placed a premium of $1.00 to $1.50 per square yard for colored asphalt in this use. Similarly, there is widespread interest in colored asphalt for limited use in directional routing on public highways. If a suitable colored material were found, it could eventually be expected to garner 5 to 10 percent of the major highway market. A premium of $2.25 to $3.50 is estimated on the basis of the relatively unsatisfactory colored materials currently in use on highways. A premium of $0.50 to $1.75 per square yard would be commanded by colored pavement in the low-volume county road market. This premium would apply to only that small friction (<5%) of this market which consists of park roads.

The strongest and most urgent demand for colored surfaces was evidenced in the paved playground market. Most public recreation officials are keenly interested in obtaining durable and economical colored surfaces. A market premium of $1.00 to $2.00 per square yard of colored surface, depending on the type of playground and its location, was indicated for 80 percent of the playground market.

Demand for porous pavement to relieve flash flooding and preserve natural drainage patterns is currently limited to less than 5 percent of the total market for parking surfaces. In this limited use, such an ecological benefit would command a premium of $1.00 to $2.00 per square yard. If, as anticipated, increasing restrictions are placed on the disposal of stormwater from large parking surfaces, the market demand for this benefit of porous pavement would increase substaintially. A premium value of $0.50 to $1.00 was placed on the use of porous pavement to preserve roadside vegetation. As discussed in Section XVI, the demand for this benefit should affect only a very minor proportion (<5%) of the parking, low-level-design residential street and county road markets. In the city residential street market where vegetation is starved by extensive paved surfaces, the demand would vary from 10 to 25 percent of the market depending on the density of development.

Because cost economies range from $1.50 to $2.40 per square yard, a demand for porous pavement to eliminate the need for curbing can be expected in 85 percent of the suburban residential street market and in 50 percent of the city residential street market. The anticipated demand is less in the city because of the substantially greater number of high traffic residential streets where the elimination of curbing might cause safety problems.

One item omitted from Table 21, which remains to be investigated, is the economic benefit of using porous pavements as a potential means for reducing the capacity of and flows to storm and combined sewer overflow treatment facilities (to be required in the near future). The savings due to the reduced cost of smaller treatment facilities and their reduced operational and maintenance costs could redound significantly to the benefit of porous pavement.

As shown in Table 21 the range of premium-commanding benefits offered by porous pavement is quite substantial. These benefits can be expected to render porous pavement economically feasible in those low-level-design uses (parking lots and playgrounds) where it is not generally cost competitive with conventional pavements, and to increase the economic advantage of porous pavement over conventional pavement in high-level-design installations.

SECTION XVIII

ADDITIONAL TYPES OF POROUS PAVEMENT

A. PORTLAND CEMENT CONCRETE STRUCTURES

Design

The object of the design study conducted for cast concrete pavement was to provide a relatively heavy duty pavement which would transmit water to the subsoil and which would store water beneath the pavement surface until percolation removed it. The appraoch taken was to design a pavement having a surface through which holes could transmit the water and a supporting structure which would also serve as a storage reservoir.

In order to avoid the use of a thick surface which would support the load but which would leave little room for reservoir capacity, it was decided that the reservoir structure beneath the surface should also serve as the main load bearing member. This consideration dictated that a web, or grid-like, structure be adopted and a trade off be made between web thickness, depth, and reservoir capacity. In addition, the size of the reservoir openings was limited by the safe span for the surface, or cover, when under load.

For test purposes a web and cover pavement was prepared. The pavement, shown in Figure 13, consists of the supporting and the surface cover. The web openings were 5 x 5 inches square and 4.5 inches deep, with a web thickness of 2.0 inches. The cover was 2.5 inches thick and contained .75 inch diameter holes which were situated over the centers of the web openings when the pavement was assembled.

Test Apparatus

In order to test the assembled pavement, the apparatus shown in Figure 14 was used. The apparatus consisted of a loading jig, test tank, and load/deflection transducers with recorder.

The loading jig was designed so that the test tank could be loaded into the jig in its entirety. Load was applied to the test pavement in the tank by means of a 5 inch diameter hydraulic cylinder, equipped with a load pad of 35 square inches.

Test Tank

The test tanks were designed for dual purposes: First, for use in load testing of pavements, and, second, for use in determining the extent of bacteriological activity beneath the pavements. The tanks were designed with slanted bottoms to collect percolated water, and with steel grid false bottoms to support the pavement and subsoil.

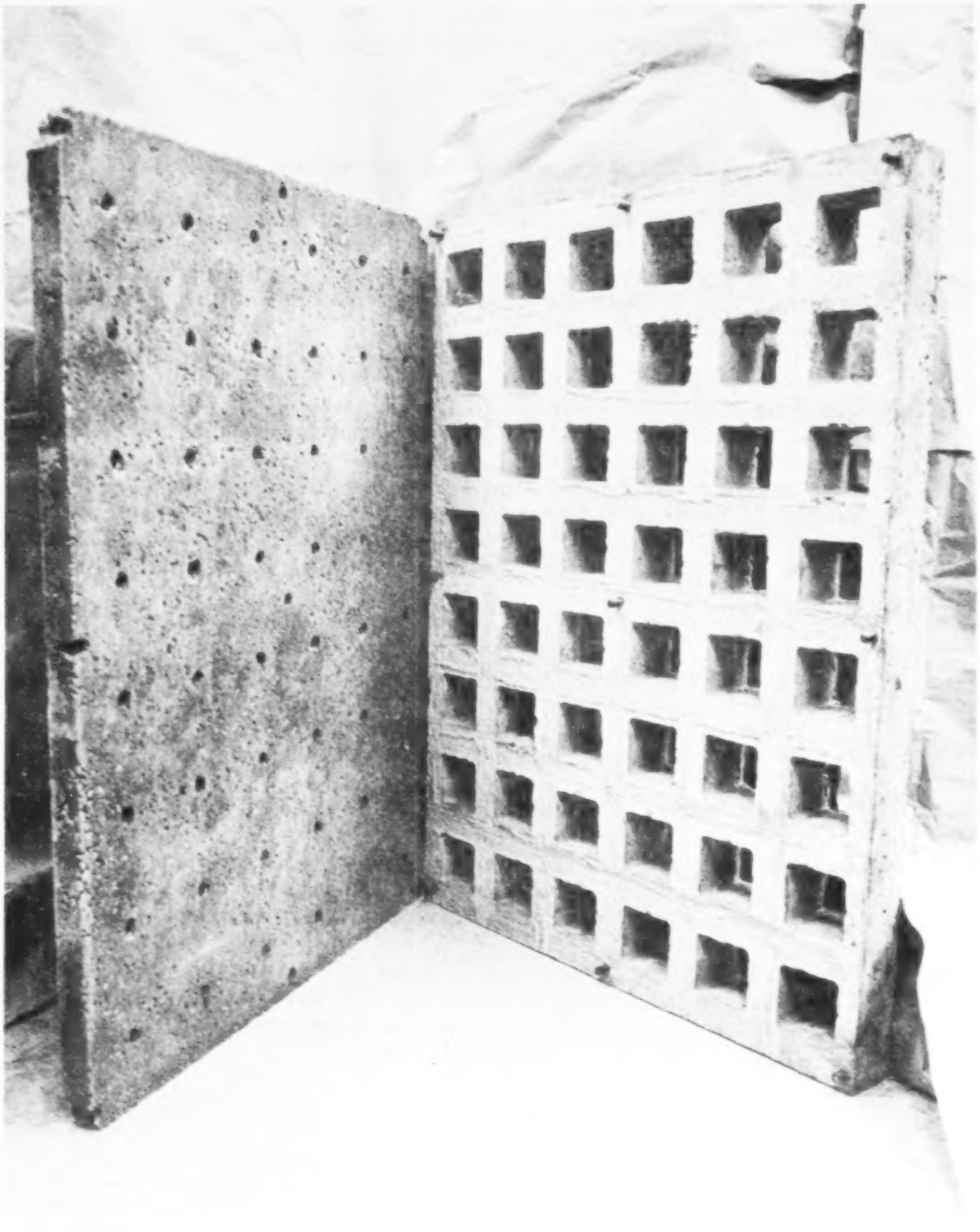


Figure 13. Web and Cover Pavement

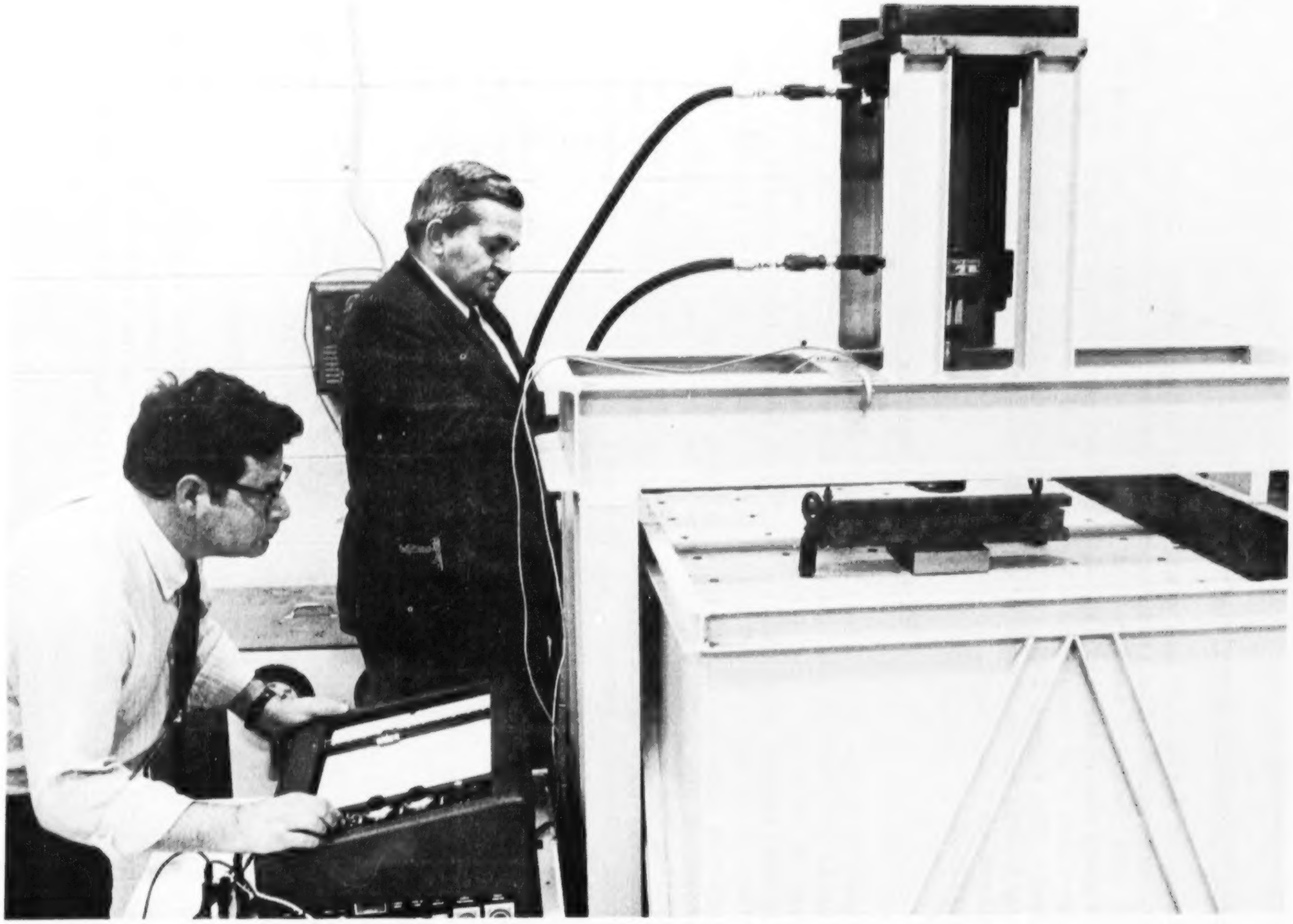


Figure 14. Assembled Pavement Test Apparatus

A three inch layer of coarse gravel followed by a two inch layer of coarse sand was placed on the grid and then subsoil of the desired thickness was added. The pavement and its base course were then applied.

Load/Deflection Transducers

Pavement deflection was monitored by using a spring loaded, linear potentiometer. The transducer was capable of resolving deflections of .001 inch. A load cell with 10,000 pounds capacity was mounted between the hydraulic ram and the load pad. The load cell read-out was capable of resolving 100 pounds load at the recorder setting used. The signal from the linear potentiometer was displaced on the X axis of an X/Y recorder while the load cell signal was displayed on the Y axis. A plot of the stress/strain curve was thus obtained.

Experimental Results

Tests with the experimental pavement were initially satisfactory but after load cycling under wet and dry conditions, cracks developed in both the cover and the supporting pattern. Loads from 0 to 6000 pounds were applied to the 35 square inch load pad in load times of 10 seconds and shock load. After each loading cycle when load was returned to zero a permanent deflection was noted. The amount of the permanent deflection per cycle decreased during dry cycling but when the pavement was wetted the deflection rose and then decreased again with successive cycles. Before the new constant value was reached, the pavement cracked. Two pavements were tested and the same crack patterns developed.

Examination of the two pavements indicated that the reason for failure was shifting and settling of the subgrade under the load application point. This led to a relatively large unsupported span at the maximum chord of the supporting web and the failure so induced in the web led to failure of the cover.

The use of a concrete pavement of the type tested is not feasible unless subsoil and base shifting can be eliminated. Further work would be required to determine whether a gravel course lightly bonded with asphalt would have the requisite stability.

B. FABRICATED PAVEMENTS

The following section of the Proposal describes approaches to porous pavements made up of factory-fabricated components, to be assembled at the road site. These were not investigated further after it was found that a less expensive open-graded asphalt concrete should be suitable.

Bricks

Pre-formed bricks, or other components which are designed to maintain large cracks between them, are laid on compacted graded gravel and the chinks between loosely filled with fine gravel (see Figure 15). Vermiculite, perlite, or other very porous minerals may be better than gravel for this purpose, and should be investigated. The bricks may be shaped or textured on the wear surface to promote water run-off and to provide skid resistance. Materials to be investigated for the bricks include modified concretes and other mineral compositions, as well as ceramic clays. The supply of the bricks in large slabs, and the handling of these by machine, is indicated to keep installation labor costs down.

As shown in Figure 15, each brick is capable of a small vertical displacement under load, and the resulting changes in void volume in the underlying gravel in dry weather should pump air into the substrate with each passage of a vehicle. An alternative arrangement (Figure 16) might be to put two holes through each brick and use rods or cords to tie large areas of brick together. In this case, spacing between the bricks could be maintained by spacers such as thick washers, if not by humps in the bricks themselves. The relative merits of this configuration, in terms of mechanical properties and air pumping, remain to be determined.

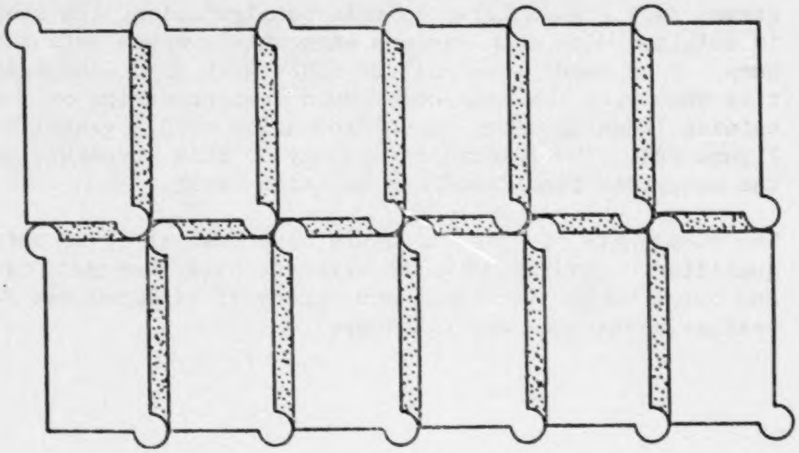


Figure 15. Bricks with Lugs to Control Spacing Between (Shaded area loosely packed with gravel)

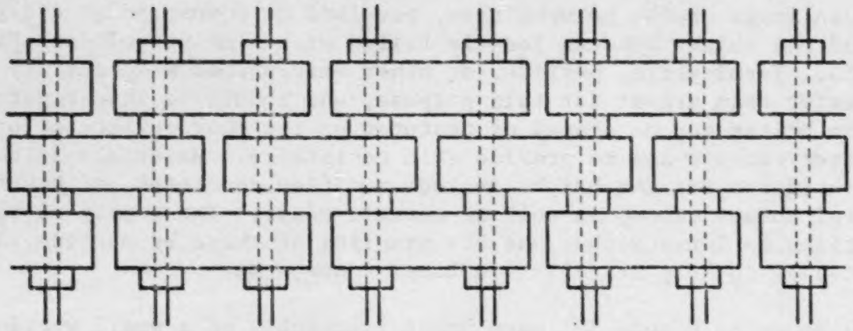


Figure 16. Bricks Assembled on Rods with Spacers Between

The first alternative has the advantage that the materials can be conventional - brick pavings have a long history - and their life and ease of repair are both known and favorable.

Honeycombs

The wearing surface is a perforated butyl rubber sheet about 1/8 inch thick. This covers a honeycomb structure which in turn rests on gravel (see Figure 17). In this configuration, the rubber sheet is deformed with each passage of a wheel, hence acts as an air pump. On a sandy loan soil or other with good load bearing properties when wet, the honeycomb could rest on strips or a sheet containing large openings, thus dispensing with a gravel subbase (see Figure 18). The reservoir capacity of this structure is within the honeycomb itself and can be quite large.

The components of this structure have been at least partially qualified: landing mats for aircraft have been made of honeycomb, and butyl rubber (in canal and reservoir linings) has demonstrated weather resistance and toughness.

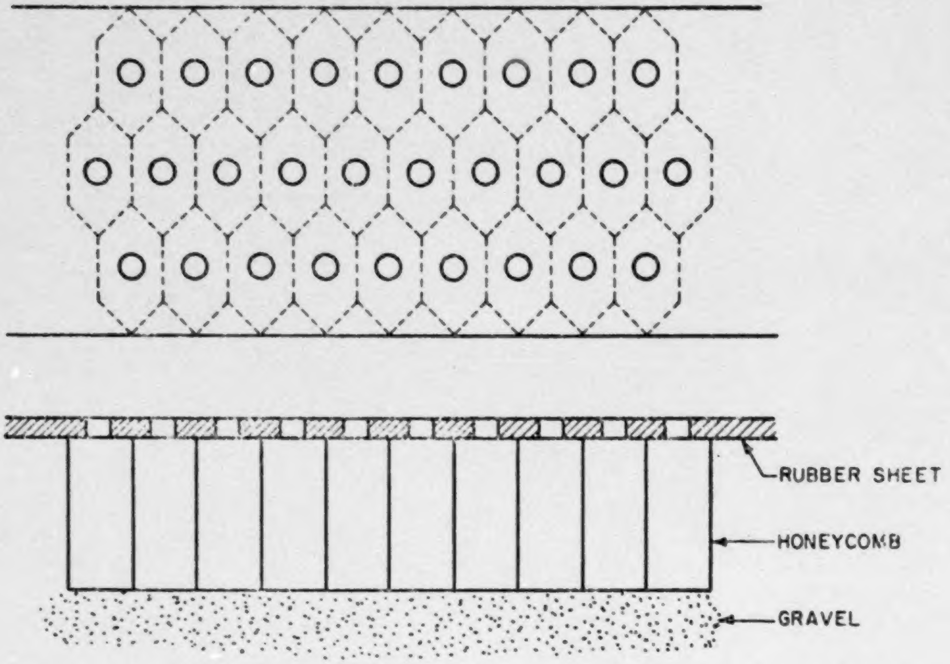

RUBBER SHEET
HONEYCOMB
GRAVEL

Figure 17. Hexagonal Honeycomb Covered with Perforated Rubber Sheet Laid Over Gravel

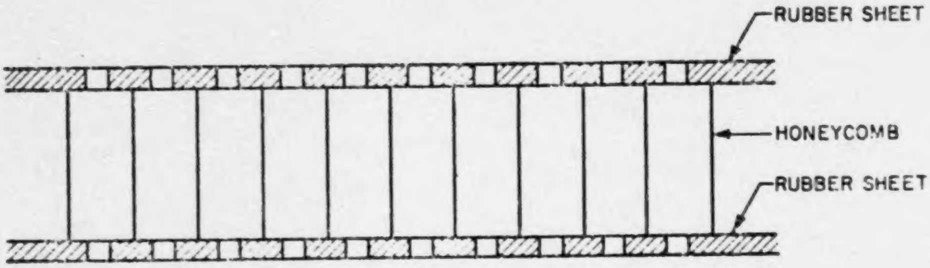

RUBBER SHEET
HONEYCOMB
RUBBER SHEET

Figure 18. Covered Hexagonal Honeycomb with Second Perforated Rubber Sheet Substituted for Gravel

SECTION XIX

PLANS FOR DEMONSTRATION PAVEMENT

SITE SELECTION FOR THE MOST PROMISING DESIGNS

(Phase B of Proposal)

Criteria for site selection will be developed. Some of them probably will be as follows:

(1) A local or state government must be willing to participate on acceptable terms.

(2) The site should be representative of many in terms of traffic and use.

(3) Weather information should be available in some detail.

(4) Soil and drainage information should be available or readily obtained.

(5) The site should be large enough to install the test pavement system and also a conventional system for comparison.

(6) The site should be accessible, to permit inspection by the public and its officials.

(7) If possible, there should be a special problem or advantage heightening the value of porous pavement at the site.

(8) Administrative and/or security provisions should be feasible for the conduct of the study and the protection of any installations of equipment or instruments.

(9) A nearby fabricator, if required, would agree to produce the pavement.

(10) Sites should be selected in various parts of the U.S., representing various climates, soils and pollutions.

It is expected that in the course of the feasibility study, the attitudes and positions of public officials will be explored, and from some of these we would expect to receive offers of cooperation.

It should not be difficult to find several candidate municipalities, and to reach an agreement in principle on the EPA terms, for one or more test sites apiece. We would then visit each site to ascertain that it presents no untoward difficulties of topography, size, drainage, soil information would be checked. These findings would be presented to the EPA for approval.

Next step would be to take soil cores for examinations, to design the pavements for the specific application, and to provide engineering specifications, complete with estimated costs. The municipality would then be in a position to negotiate a grant with EPA, and to arrange for the construction. We will consult as necessary during these processes.

Included in the specifications would be provisions for instrumentation as described under Phase C. The size of the site is determined in part by the monitoring and test requirements. A preliminary estimate for a parking lot or shopping center is that the porous pavement could occupy a four-acre square with one drain in the middle, by which run-off, if any, can be measured. Beside this would be another four-acre square with a drain in the center, covered with conventional pavement, for a control.

EVALUATION OF DEMONSTRATION PAVEMENTS

(Phase C of Proposal)

The test pavements and their controls should be monitored for a full year, to determine the effects of all seasons. Monitoring steps are:

(1) At each site there will be automatic monitoring of weather (temperature, wind, and precipitation) together with runoff from the test pavement and the control pavement and water level in the porous pavement (see below). The difference in run-offs should be equal to the amount imbibed by the porous pavement.

(2) Each site will be visually inspected twice a month to ascertain any damage, cleanliness, evidences of change, etc. During several storms, an observer will note how the traffic proceeds, and how the pavement operates.

(3) At two locations in each test pavement and control pavement, strain gauges just under the surface of the pavement will measure its deflection, and FILPIPS (stress sensor) on the soil under the gravel course will measure load. A standard vehicle will pass over these instrumented sections on occasion to measure load distribution and deflection as affected by wetness of the soil, temperature and age. On accasion, vehicles of different weights will be used.

(4) At two locations near the center of each test pavement, casings several feet deep (2 different depths) will permit taking samples of water that has percolated through the pavement and soil. These will be checked for pH, coliform bacteria, oils, lead and solids. If possible similar samples will be taken from similar installations

in a nearby large lawn or field, and run-off samples from the pavements also will be checked.

(5) At two other locations in each porous pavement, a perforated pipe will pass through to the soil. In this pipe the level of water in the reservoir layer can be gauged and samples of soil taken for bacterial cultures.

(6) Experiments will be run with sweepers and vacuum cleaners to ascertain their efficiency in picking up trash and any effect they may have on the pavements.

(7) Controlled contamination may be washed through the pavement deliberately to see how it affects the purity of the percolated water. At the end of the year, sections of pavement can be removed and examined for contamination.

(8) Safety aspects of the wet and dry pavement, such as breaking distances, skidding on curves, etc. will be ascertained. Photographic evidence may be obtained, to be shown to safety officials and others.

(9) Drivers, passengers, pedestrians and local residents will be interviewed to determine public reactions to the new pavements.

On each site will be a monitoring cabinet and weather instruments as required in item (1). Items (3), (4), and (5) require installations in the pavement where recorders will be connected during testing or where grab samples will be taken. Items (2), (6), (7), and (8) represent ad hoc activities to be carried out on the site. Figure 19 illustrates the sampling arrangements.

The final report on each demonstration pavement will show, by means of data and observation:

(1) Its adequacy to imbibe water and avoid run-off.

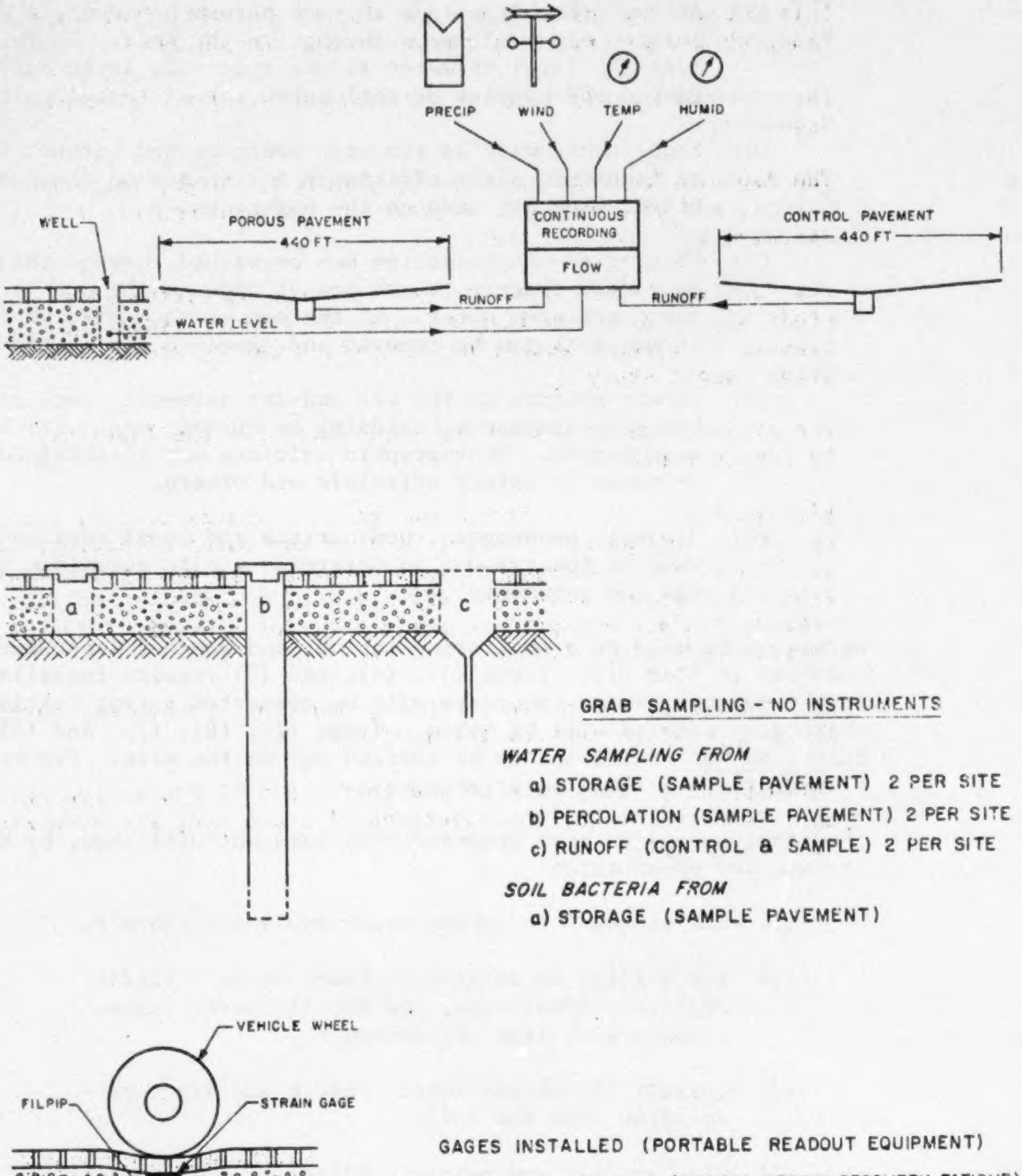
(2) Its ability to survive weather, loads, traffic, and other conditions, and how its performance changes with time and season.

(3) Quality of imbibed water, before and after percolation into the soil.

(4) Cleanability and maintainability.

(5) Effects of pollution.

(6) Judgements of comfort, esthetics, quietness, safety, etc.


PRECIP
WIND
TEMP
HUMID
CONTINUOUS RECORDING
FLOW
WELL
POROUS PAVEMENT
440 FT
CONTROL PAVEMENT
440 FT
RUNOFF
RUNOFF
WATER LEVEL
a
b
c
VEHICLE WHEEL
FILPIP
STRAIN GAGE

GRAB SAMPLING - NO INSTRUMENTS

WATER SAMPLING FROM

a) STORAGE (SAMPLE PAVEMENT) 2 PER SITE

b) PERCOLATION (SAMPLE PAVEMENT) 2 PER SITE

c) RUNOFF (CONTROL & SAMPLE) 2 PER SITE

SOIL BACTERIA FROM

a) STORAGE (SAMPLE PAVEMENT)

GAGES INSTALLED (PORTABLE READOUT EQUIPMENT)

MECHANICAL TESTING (STRESS, STRAIN, RECOVERY, FATIQUE)

4 SITES (2 TEST PAVEMENT, 2 CONTROL)

Figure 19. Test at Site

SECTION XX

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The project was conceived and supervised for The Institute by Edmund Thelen.

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SECTION XXII

GLOSSARY OF TERMS RELATING TO PAVEMENT

Aggregate - rocks, usually crushed, of specified size distribution and durability properties.

Aggregate, coarse - retained on #8 sieve.

Aggregate, fine - passes thru #8 sieve.

Asphalt, asphalt cement - a black, viscoelastic, waterproof residue from the distillation of petroleum. It also occurs naturally in some parts of the world.

Asphalt Concrete - A paving material consisting of aggregate bound with asphalt, made by heating both materials to around 300°F, followed by mixing, delivering, spreading, and compacting while still hot.

Bituminous - a class of materials of a pitch-like nature, including asphalts, coal tars, pitches, etc.

California Bearing Ratio (CBR) Test - Quantifies the load-bearing capacity of a soil on a scale ranging from zero (no capacity) to 100, which is the load-bearing capacity of crushed stone.

Cutback - asphalt dissolved in a petroleum distillate, which evaporates after laying, as the asphalt "sets".

Dense graded - Usual aggregate distribution, with enough fine particles to reduce the void volume to below 4% in an asphalt concrete.

Durability test - As used in this report, a test to determine the extent to which the asphalt in a porous pavement hardens when air at 140 or 150°F is passed thru the pavement for several weeks.

Emulsion - A suspension of asphalt particles, generally 1 to 2 microns in diameter, in water. Generally contains 55-62% asphalt by weight.

Freeze-thaw test - A test in which the pavement is filled with water, drained, cooled to 0°F and the heated to 50°F. This cycle is repeated enough times to simulate the temperature cycling naturally occurring during years of service.

Gradation - The distribution of particle sizes in aggregate.

Marshall test - ASTM Test D-1559. A test for measuring the load required to crush a standard cylinder of pavement, and the degree of deformation, or flow, at which the cylinder ruptures.

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Open graded - Aggregate containing relatively small amounts of fine particles. Generally contains over 10% by volume of voids in an asphalt concrete.

Pavement - A durable, tough layer of material subjected to vehicular or pedestrian traffic. Normally it is relatively waterproofed.

Permeability Coefficient - The volume of water, in cubic feet, under a head of one foot, that will pass thru a square foot of porous surface in 1 day.

Penetration test - ASTM Test D-5. A means of determining the hardness of bituminous materials by measuring the distance a standard needle will penetrate into them in a given time, under standard load and temperature. Usually 5 seconds, 100 grams, 77°F. Asphalt grade 85 to 100 pen. means the needle will penetrate from 0.85 to 1.00 centimeters.

Porous pavement - A pavement through which water can flow at significant rates.

Seepage rate - Calculated from the permeability coefficient, is the inches of rain that would pass through the pavement in one hour, with no water standing on the surface. A head exists due to the thickness of the pavement.

Stripping - The tendency of water to displace asphalt from stone. Stones vary in their stripping resistance and anti-stripping agents are added to the asphalt if the stone is deficient in this respect.

Subbase - A bed of aggregate under the pavement, which helps to distribute wheel loads over the underlying subgrade. This aggregate sometimes is lightly bonded with asphalt.

Subgrade - The soil under the subbase. If the soil naturally occurring at the site is deficient in load bearing capacity it may be treated or replaced.

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Porous Pavements

27 *Abstract*

Laboratory studies demonstrated the technological and economic feasibility of open-graded asphalt concrete as porous pavements to conserve water, to reduce loads on combined sewers and treatment plants, and to mitigate urban runoff as a destructive environmental factor.

The disposal of demolition wastes in these pavements is a plus factor.

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